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(NASA CR-51304; Technical Memorandum ~~No~~. 33-25)

DESCRIPTION AND EVALUATION OF ANGULAR ENCODING SYSTEMS UTILIZED BY GOLDSTONE TRACKING ANTENNAS

M. Perlman Nov. 30, 1960 c ref

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JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA
November 30, 1960

February 21, 196[illegible]

Recipients of Jet Propulsion Laboratory
Technical Memorandum No. 33-25

SUBJECT: Errata for Technical Memorandum No. 33-25

Gentlemen:

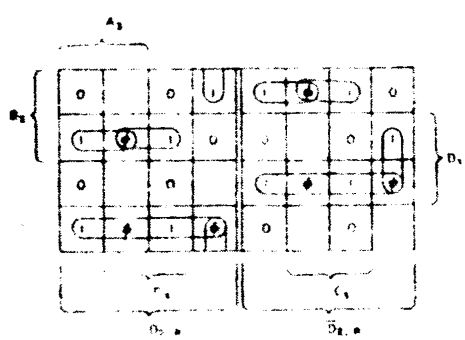
It is requested that the following changes be made in your copy of JPL Technical Memorandum No. 33-25, entitled "Description and Evaluation of Angular Encoding Systems Utilized by Goldstone Tracking Antennas," by M. Perlman, dated November 30, 1960:

Page [illegible], lines 30 and 31: change [illegible] from east to west about PQ. The [illegible] Earth's precession and nutation phenomena (Ref. 4)."

Page 30, line 38: for "[illegible]00110" read "[illegible]."

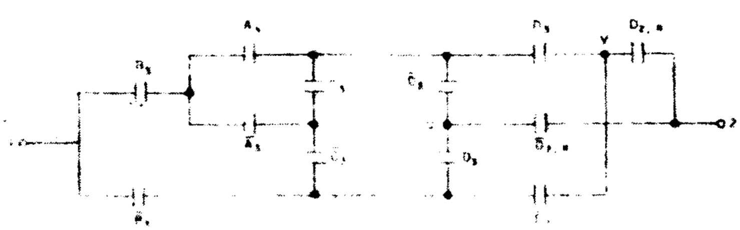
Page 30, line 41: for "1000[illegible]0101" read "100000[illegible]0101."

Page 68: first sketch is changed as follows:



Page 68, line 2: for "$D_2(B_1 + A_1C_3)$" read "$D_2(B_1 + A_1C_3)$."

Page 68, [illegible] sketch [illegible] V [illegible]



Very truly yours

N. F. White, Assistant Manager
Technical Reports Section

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ACKNOWLEDGMENT

The following Jet Propulsion Laboratory and Datex Corporation personnel made especially valuable contributions to the Goldstone angular encoding effort.

Jet Propulsion Laboratory

Richard M. Beckwith designed and developed precision test fixtures, mechanical indexers, and many mechanical innovations with unique application of flexures.

Richard J. Howell machined and assembled the precision mechanical components designed at JPL.

Warren R. Dickerson made the optical measurements which established system accuracies and limitations.

David P. Willoughby executed the illustrations with special emphasis on engineering detail.

John H. Brittcliffe, with the help of William Marburger, operated and serviced the equipment in the field.

Robert V. Powell proofread the text of this report and made pertinent alterations and corrections.

David M. Scaff, William N. Cook, and George K. Davis contributed, respectively, liaison work, fabrication of electronic test units, and the drawing of schematic diagrams.

Datex Corporation

George Canova, George Cline, Dick Bazard, Bill Duncan, Harvey Crist, Brigne Latham, Adrian Elich, Al Mahoney, and Howard Wood were among those responsible for the original design, fabrication, and installation of encoding equipment. The author wishes especially to thank George Canova, Datex Senior Project Engineer, for his unstinting efforts and cooperation.

I. INTRODUCTION TO ANGULAR ENCODING

An angular encoder (or digitizer) may be considered a member of a particular class of transducers (mechanical-to-electrical) which ultimately delivers a digital representation of an angular position (Ref. 1). Because combinations of two-level electrical signals provide the means of indicating the numerical value of an angle, and because electrical signals are inherently adaptable to communication links, control, computing and data processing, the output of an angular encoder will usually be electrical.

The angular positions that a shaft can assume when rotated from a zero referenced position (within a single revolution in either direction) are theoretically infinite. For this reason it would appear that the electrical output should be analog (continuous) rather than digital. In addition to the fact that the digital representation is superior to the analog representation in terms of potential accuracy, the digital method also possesses the following advantages: An analog signal undergoes serious deterioration when processed (e.g., recorded), used for computing, or transmitted for even relatively short distances. In contrast, the two-level combinations of electrical signals are immune to degradation of quality in each of the three above cases.

Realizable signal-to-noise ratios restrict the accuracy (sensitivity) of the analog form of output. In a digital output, the amplitude of noise merely dictates the difference in amplitude between the two electrical signals (or pulses), one of which may have zero amplitude (or absence of a pulse) regardless of the significance of the digit the two levels represent. Error due to quantizing (Ref. 1, 2), rather than the realizable signal-to-noise ratio establishes the limits of accuracy for digital outputs. When the accuracy required is better than 1 part in 1000 absolute, economics dictates digital representation. To preserve the accuracy of an analog representation, an analog-to-digital conversion is made before transmission, computational operations, or data processing.

To date, absolute accuracies of 1 part in 2^{21} (2,097,152) have been attained in angular encoding. The terms "absolute accuracy," "resolution," and "quantization," among others commonly used with reference to angular encoding, will be defined in a later section.

II. OBJECTIVES

The Goldstone tracking complex presently consists of one receiving and one transmitting antenna located approximately 6.5 air miles apart. Each antenna has an 85-ft-diameter parabolic reflector mounted on two orthogonal axes. The pointing direction of each antenna (i.e., the direction of the axis of revolution of the generated paraboloid) together with range information determines a point in space. The most practical method of determining the pointing direction is to measure the angular displacement about each of the orthogonal axes of rotation of the parabolic reflector. Regardless of the accuracy of these angular measurements, the direction of the radio frequency energy (transmitted or received) has uncertainties, since the direction of the r.f. axis and the paraboloid's axis of revolution do not necessarily coincide. Careful design of the antenna and location of the r.f. feed cannot completely eliminate the uncertainties brought about by mechanical sag in the antenna structure, effects of temperature variation, mechanical hysteresis, etc. In addition, the rotation of the antenna about one axis has an effect on the angular position about its orthogonal mate. This "mechanical crosstalk" is a function of pointing direction and represents another source of uncertainty. When measurements for system accuracy evaluation purposes are made, the accuracy of measurement should be such that it causes no appreciable degradation. This calls for a statistical accuracy of measurement approximately 5 to 10 times greater than the known accuracy of the quantity to be measured.

Since each antenna's pointing accuracy when measured at the orthogonal axes was an unknown, engineering judgment prevailed in deciding the required encoding system accuracy. It was felt that the angular position of each of the orthogonal axes would have an uncertainty of 1 mil (200 sec of arc or 0.056 deg) rms. This resulted in the specification of 0.1 mil (20 sec of arc or 0.0056 deg). To allow for future improvement in the antenna structure, an angular encoding accuracy design goal of 0.05 mil was established. The pointing accuracies above were assumed for the receiving antenna in an r.f. lock mode of operation in which the r.f. axis is made to seek and follow the center of the received r.f. energy. Thus, the alignment uncertainty of the mechanical and r.f. axes contributes to the total uncertainty. The transmitting antenna was assumed to have approximately the same overall pointing accuracy when measured at the orthogonal axes.

The digital representations of the angular displacement about the two orthogonal axes of each antenna are used for two purposes:

1. To provide, in conjunction with data handling equipment, permanently stored, time-tagged, angular components of each antenna's pointing direction.
2. To enable each antenna to be slaved to digital pointing commands when acquiring a space probe, and to link the antenna via a coordinate converter in a master-slave mode when tracking a space probe.

The antenna mounts and associated angular coordinates of pointing direction are discussed in Section III.

III. ANGULAR COORDINATE SYSTEMS OF THE GOLDSTONE ANTENNAS

A. Receiving Antenna

One of the orthogonal axes of the Goldstone receiving antenna (Ref. 3) is fixed and parallel to the Earth's rotational axis. The angular displacement about this axis, commonly called the polar axis, is one of the encoded angular coordinates, and it is termed hour angle or, more specifically, local hour angle. The orthogonal mate of the polar axis is not fixed and rotates in a plane perpendicular to the polar axis. It is referred to as the declination axis. Angular displacement about this axis is termed declination and is encoded to provide one of two angular coordinates. A scaled drawing of the receiving antenna appears in Fig. 1.

The coordinate system in which the receiving antenna operates is the equatorial system used by astronomers. An imaginary sphere on whose inner surface all astronomical bodies appear to observers on Earth is used to locate a point in space. This celestial sphere has as its center the Earth's center. The radius of the celestial sphere is arbitrary; however, it is infinitely larger than the Earth's radius. The points where the Earth's axis, imaginatively extended, would pierce the celestial sphere are called the north and south celestial poles. The locus of all points on the sphere equidistant from the celestial poles is the celestial equator. Great circles passing through the celestial poles, designated hour circles, serve a similar role as the Earth's meridians.

Points on the surface of the Earth are referenced to two principal great circles, the Greenwich meridian and the Earth's equator. The specification of spacial points on the celestial sphere is fundamentally the same. Particular great circles are chosen as references for each of several coordinate systems (Ref. 4).

In the equatorial system, the celestial equator and the hour circle (the projection of the observer's meridian onto the celestial sphere) serve as references. The observer's celestial meridian is a name often used for the reference hour circle. Local hour angle ψ of a spacial point is specified by the angle between the observer's celestial meridian and the celestial meridian (hour circle) passing through the point. The local hour angle must be time-tagged to account for the Earth's rotation. It increases from 0 deg at the observer's celestial meridian in a westerly direction to 360 deg. In Fig. 2, arc RD of the celestial equator represents the local hour angle ψ of point V. The declination δ of the point is not dependent on the Earth's rotation and is specified by the angle between the celestial equator and the parallel of declination (small celestial circle parallel to the celestial equator) on which the point lies. The declinations of the south celestial pole and the north celestial pole have been defined (for Goldstone) as 270 and 90 deg, respectively. The declination of points lying on the celestial equator is 0 deg. Thus the declination of a point moving from the south celestial pole to the north celestial pole would increase from 270 to 360 (or 0) to 90 deg. In Fig. 2, arc DV represents the declination δ of the point V. The time-tagged local hour angle and the declination determine a point in space.

Since the receiving antenna has its polar axis aligned parallel to the Earth's rotational axis and its declination axis perpendicular to the polar axis (and hence the Earth's rotational axis), the encoded angular displacements about these axes are angular coordinates in the equator system. The receiving antenna structure is often referred to as an equatorial or polar mount.

Introducing the observer's latitude, zenith, and horizon to a pictorial representation of the equator system adds to its physical significance. The latitude of the station affects the angle between the polar axis and the local horizon plane. For example, the polar axis of an equatorial mount located at the north geographical pole would be perpendicular to the Earth's surface, whereas, at the equator, it would be parallel. The zenith of an observer on the Earth's surface is the point on the celestial sphere which is directly overhead. Its direction can be established approximately by means of a plumb line.[1] The unobservable point on the sphere directly underfoot is called the nadir. The locus of all points equidistant from the zenith and nadir and lying on the sphere is designated as the celestial horizon. The local horizon plane of the observer (perpendicular to the plumb line) is parallel to the plane in which the celestial horizon lies. The angle between the zenith and the

[1]The plumb line approximates the local vertical since it includes the effects, though small, of (1) the oblateness of the Earth, (2) the Earth's rotation, and (3) the nonuniform distribution of land masses.

celestial equator is equal to the latitude ϕ_0 of the observer. Great circles which pass through the zenith and nadir are analogous to hour circles and are called vertical circles (see Fig. 3). (Note that the celestial equator intersects the celestial horizon at its east and west cardinal points. The north and south cardinal points of the celestial horizon are those points nearest the north and south celestial poles, respectively.)

Since the overall pointing accuracies of the antennas are determined optically by star tracking (Ref. 3), it is worth noting how the observed position of a star varies. Because of the rotation of the Earth, there is an apparent rotation of the celestial sphere from east to west about PQ. The declination of a star when precesion and rotation phenomena (Ref. 4) are neglected appears fixed owing to its great distance from Earth. Therefore, as shown in Fig. 3, a star designated Xdescribes a small circle LXM which is a parallel of declination. The star is said to culminate or transit (Ref. 4) when crossing the observer's celestial meridian. Here, at L, its distance from zenith is at a minimum. It crosses the celestial horizon at F, where it appears to set. Its lowest point (below the horizon) is M and it returns above the horizon at G, where it is said to rise. Because of a star's fixed declination, an equatorially mounted antenna is not driven about its declination axis when tracing a star.

B. Transmitting Antenna

One of the transmitting antenna's orthogonal axes is fixed and perpendicular to the local horizon plane. The angular displacement about this axis, designated as the azimuth axis, is one of the encoded angular coordinates, and is termed aximuth. The orthogonal mate of the azimuth axis is not fixed and rotates in a plane perpendicular to the azimuth axis. It is referred to as the elevation axis. Angular displacement about this axis is termed elevation, and it is encoded to provide one (of two) angular coordinates. A scaled drawing of the transmitting antenna appears in Fig. 4.

The coordinate system in which the transmitting antenna operates is the horizon system used by astronomers. The principal great circles are the celestial horizon and an arbitrarily chosen vertical circle. At Goldstone, the vertical (semi) circle passing through the north celestial pole was selected as a reference. It intersects the local horizon plane at the north compass point. The azimuth of a spacial point is specified by the angle between the reference vertical circle and the vertical circle passing through the point. It increases from 0 deg in the direction of due north to 360 deg in a direction which is initially easterly. In Fig. 5, arc NESH represents the azimuth of point V. The elevation (often referred to as the altitude) ρ of the point is specified by the angle between the celestial horizon and the parallel of elevation (small celestial circle parallel to the celestial horizon) on which the point lies. Both azimuth and elevation angles must be time tagged to account for the Earth rotation. The elevation of zenith and nadir has been defined (for Goldstone) as 270 and 90 deg, respectively. The elevation of points lying on the celestial horizon is 0 deg. Thus the elevation of a point moving from nadir to zenith would increase from 270 to 360 (or 0) to 90 deg. In Fig. 5, HV represents the elevation ρ of point V; HV is an arc of the vertical circle passing through point V. Time-tagged azimuth and time-tagged elevation (angles) determine a point in space.

Since the transmitting antenna has its azimuth axis coinciding with a plumb line and its elevation axis perpendicular to the azimuth axis, the encoded angular displacements about these axes are angular coordinates in the horizon system. The transmitting antenna structure is commonly called an Az-El mount. Unlike the polar mount, the azimuth axis is always perpendicular to the Earth's surface regardless of the antenna's location. A star which moves on a parallel of declination would have its elevation as well as azimuth continually changing when observed from Goldstone.

In Fig. 6, contours of constant local hour angle and declination components of the receiving antenna's pointing direction are shown. Superimposed contours of constant azimuth and elevation components of the transmitting antenna's pointing angles also appear. These contours are associated with points in space 100 miles or more away. The following should be noted:

1. Scaled separation of the antennas.
2. Reference local hour angle and azimuth.
3. Orthogonality of contours of angular components in the same coordinate system.
4. Receiving antenna's mechanical travel limits.
5. The local horizon mask (surrounding mountains, etc.).

Figure 7 illustrates Goldstone local hour angle (GoLHA), declination (Goδ), azimuth(GoAZ), and elevation(GoEL)angular measurements.

C. The Time Dimension

Because of the apparent rotation of the celestial sphere (due to the Earth's rotation) the angular coordinates of a spacial point must be accompanied with the time of observation. Even a cursory discussion of time and its measurement is beyond the scope of this report (see Ref. 4-6). Though the time-tag at Goldstone is referred to as Greenwich mean time (GMT), it more correctly should be termed Universal Time (UT) or Uniform Solar Time. The Goldstone digital clock is periodically compared with time ticks from WWV, a standard frequency and time (UT) station.

D. Definitions

A comparison of encoding systems is meaningful only if their characteristics are referenced to the same set of definitions. This is particularly true of accuracy specifications. The definitions that follow apply to linear angular encoding and do not necessarily agree with those used by some manufacturers.

Maximum count: The total number of distinct combinations of two-level electrical signals in the encoding system's output.

Least count: The smallest numerical value represented by one of the combinations of the above.

Quantum: The least count often expressed as the smallest distinguishable angular change of the encoded shaft. This angular change is represented by the difference between successive count transitions.

Resolution: The smallest distinguishable angular change of the encoded shaft, thus a quantum. It is also expressed as the ratio of one count over the total count to denote the fineness of quantization (Ref. 7) in the conversion process (i.e., of a shaft rotation to a digital representation).

Quantizing: The representation of the amplitude of a continuous phenomenon (e.g., voltage variation, shaft rotation) by discrete electrical levels or combinations of two-level electrical signals.

Quantization error: The undetectable variation of an encoded shaft's position due to its discrete characterization. Error due to roundoff in numerical calculations and error due to quantizing are synonymous. This variation, inherent in all systems employing digital techniques, gives rise to a maximum error (or uncertainty) of ± 1/2 quantum. Quantization noise (so called because of its random nature) is directly proportional to the quantum (size).

Accuracy, absolute: The maximum error that can be encountered in an encoding system's output representation in terms of the ratio of a plus or minus quanta error (plus or minus degree error) over the total quanta (360 deg). The absolute accuracy includes the unavoidable quantization error in addition to the encoding system's errors. In an ideal encoding system, the absolute accuracy would be ± 1/2 quantum (quantization error) over the total quanta.

Accuracy, rms: The root-mean-square accuracy is statistically determined from n measurements of the encoded shaft's angular displacement for corresponding encoder count outputs. In essence it is a measure of the likelihood of the encoding system's output errors falling within particular bounds. The following equations, discussed in more detail in Section V, are used in calculating rms accuracy:

$$x^* = \frac{1}{n} \sum_{k=1}^{n} (x_{ks} - x_k) \tag{1}$$

$$s^* = \sqrt{\frac{1}{n} \sum_{k=1}^{n} \left[x^* - (x_{ks} - x_k) \right]^2} \tag{2}$$

where

x_{ks} = kth reading of the angle represented by the encoder count output

x_k = kth reading of the angular displacement of the encoded shaft (where the measuring device's inaccuracy is negligible compared to that of the encoding system)

x^* = sample mean error

s^* = rms accuracy (or error) about the sample mean error

n = total number of readings, $n >> 1$

The sample mean error (1), an arithmetic average of the errors found at n measured points, is a bias which can be removed from the system. The rms error, which is a measure of dispersion of errors, is unaffected by the sample mean.

Repeatability: The maximum difference between any two (of many) encoder count outputs representing repeated and identical angular settings of the encoded shaft.

The system error for a given encoded shaft setting is generally a combination of a random or stochastic component and a systematic or predictable component. Repeatability is affected by the random component only, whereas accuracy takes into account both the random and systematic errors. Therefore, quantitatively, repeatability will be smaller (or better) than accuracy.

E. History of Angular Encoding at JPL

In May, 1958, a survey of angular encoding techniques and equipment was made; the results of this survey were used in selecting the angular encoding system for the Juno II program involving the tracking of a radio beacon in a lunar probe. The 85-ft parabolic receiving antenna (HA-DEC) and a 10-ft parabolic, modified Nike (Az-El) antenna were encoded to provide decimal angular data for teletype transmission. One-to-one speed shafts for each of the axes were not readily available. Limited time and budget prevented the incorporation of 1:1 speed shafts. Coupling of an encoding transducer to a shaft geared to the axis became necessary. For this reason inherent gear inaccuracies were present before the design of angular encoding began. Therefore, only the accuracy of the transducer could be specified (consistent with the accuracy of the shaft to which the encoding transducer is coupled when referenced to the encoded shaft).

The considerations above led to the following specifications for the encoding transducer (identical for all axes):

1. Gearing between the encoded shaft and the encoding transducer's mechanical input: assumed 45:1 step up.
2. Transducer count output: 0 to 89,999 in increments of 1 count.
3. Encoding system output: 000.000 to 369.994 deg in increments of 000.004 deg.
4. Form of output: binary - coded decimal (see Appendix A).
5. Maximum readout command rate: 1 per sec.
6. Maximum angular rate of shaft to be encoded: 1° per sec.

(Note that the decimal point is fixed and is not part of the output.)

The survey revealed that angular encoding transducers in wide use at the time fell into one of three categories:

1. Phase shift encoding. Here the phase of a periodic waveform is shifted proportionately to a shaft rotation and this phase shift is measured by digital techniques. The Colorado Research Corporation has developed an encoding scheme of this type that

realizes an accuracy of 1 count in 2^{21} counts. (See Ref. 8 for a description of an early version.)

2. Encoding with optical disk patterns (Ref. 1). Optical encoding employs a lamp light passing through a slit which strikes an optical pattern made up of opaque and translucent segments. Photocells on the opposite side of the disk convert the light energy passing through translucent segments to electrical energy. The optical pattern is coded as a linear or nonlinear function of the shaft position. By using a flashing light source, a higher signal-to-noise ratio results, ac coupling can be used with the photocell amplifiers, and a higher light intensity without increased heating (input power) is realized. Diffraction problems give rise to slit width (narrowness) limitations which in turn limit the smallness of the pattern segment width. The Baldwin Piano Company had successfully produced an 18-digit encoder having an accuracy of ±1 count in 2^{18} counts. It is a single turn, 21-in.-diameter encoder (including housing) weighing 165 lb less the high-voltage lamp pulser.

3. Encoding with conducting and nonconducting segmented (electro-mechanical commutator type) disk patterns (Ref. 1). This type of transducer has conducting and nonconducting zone patterns analogous to the opaque and translucent optical patterns. Brushes riding on these segmented zones serve the same role as monochromatic light passing through the slit in the optical transducer.

Physical limitations in minimum brush and segment widths restrict the resolution of commutator-type encoding disks of a given size. An increase in the physical size of the optical and commutator disks permits an increase in resolution (for the minimum segment width). There is, however, the point where introduced mechanical inaccuracies more than offset the increased resolution and ideal accuracy realization. As indicated in Ref. 1, resolution, segment ruling accuracy, and brush widths in the case of commutator-type encoding disks do not favorably compare with their counterparts in optical disks. The single-turn, commutator-type encoding disk with the highest resolution was formerly manufactured by the Datex Division of the G. M. Giannini Company. The resolution was 2400 counts per turn for a 6.125-in.-diameter encoder (including housing) weighing 2.125 lb. Recently, the Datex Corporation (now an autonomous subsidiary of the Giannini Controls Corp.) achieved a single-turn resolution of 4096 counts on a 3-in. disk (commutator type). Step-up gearing between the shaft (to be encoded) and the encoding disk results in an increased system resolution, since a count (or quantum) would represent a smaller shaft rotation. The system inaccuracies would, of course, include gearing inaccuracies. Because of the relatively low inherent resolution of the commutator-type encoding disks, step-up gearing is employed. Reflected inertias (proportional to the square of the gear ratio) and speed limitations as well as introduced inaccuracies must be considered in geared encoding system designs. Also, a coarse or low-count encoding disk, geared 1:1 to the encoded shaft, is needed to keep track of the code cycles (whenever it exceeds one) of the fine or high count encoding disk. Fortunately, electronic gearing (servo repeaters) can be employed to improve gearing accuracy and torque requirements.

The three types of transducers were compared in terms of cost, availability, resolution, required accuracy (static and dynamic), life expectancy, and reliability based on data in a field operation environment.

The commutator-type transducer was chosen because of its low cost, availability, simplicity of associated logic, adequate resolution and accuracy in geared systems, and proven reliability in the field. (The Datex Corporation was selected to design and fabricate the angular encoding systems.) Another important consideration in encoding is the mechanical coupling between the transducer and its input. Longitudinal, angular, and radial offsets between the mechanical input to the transducer and the transducer itself require a method of coupling to minimize encoding errors. Radial offsets (eccentricity) resulting in a relative displacement between the brushes and the disk can seriously degrade the accuracy. Datex has incorporated an effective integration of the shaft which provides mechanical input with the encoding disk assembly. The disk is mounted on a hollow shaft and rotates under brushes mounted on a housing; the rotation of the housing is restricted. The entire assembly slides onto the shaft providing mechanical input and is free to move radially in such a manner that no appreciable relative displacements of the disk and brushes result from eccentricity.

The *Nike* antenna had available 5:1 (precision) speed shafts for each axis. An additional 9:1 precision gearing for the fine disk (2000 count) was utilized to obtain a 45:1 step-up for each axis to be encoded. This resulted in the specified 90,000 count (or 000.004-deg resolution) per 360 deg of rotation about an axis. At Goldstone, servo repeaters were used to link the disks to two-speed synchro sensors. In an effort to satisfy the *Juno II* program time scale and budget, the sensing and 45:1 step-up gearing took place at the pinion drive for each axis of the Goldstone receiving antenna. This unfortunately introduced gear (pinion and bow) inaccuracies for both axes. Star tracks revealed enough information about the repeatable gear errors to enable a general-purpose digital computer to remove the majority of them from measured trajectories derived from *Pioneer III* and *IV*. The star track evaluation data used in the encoding systems are shown in Ref. 3.

A T-2 Wilde theodolite (2 sec of arc, absolute accuracy) and a Hilger and Watts clinometer (approximately 6 sec of arc, absolute accuracy) were used to determine the rms accuracy of the azimuth and elevation encoding systems of the modified *Nike* antenna.

Overall azimuth and elevation encoding accuracies of 38 and 36 sec (rms) of arc were measured. This included the inaccuracy effects of 5:1 gearing in the *Nike* pedestal, the added 9:1 precision gearing, quantizing, and the fine encoding disk. No overall accuracy tests were made for the encoding of the Goldstone receiving antenna since the servo repeaters (also used in the power servo control system) were not available until installation. Since the dynamic accuracy of the servo repeater of the

Goldstone antenna was comparable to that of the precision gearing in the Nike antenna, an overall estimate of 40 sec of arc of rms accuracy was realistic. These results were encouraging and led to the specifications of a new and improved encoding system for the receiving antenna. In order to better evaluate the antenna's pointing accuracy and capitalize on an increased potential encoding accuracy, sensing of angular rotation about an axis was to be moved to the axis in question. This would also place the pinion and bow gear within a servo drive loop, enabling a comparison of a digital angular command with a present encoded angular position about an axis. Identical systems were planned for the yet unconstructed 85-ft parabolic transmitting (Az-El) antenna described in Section III-B. Upon satisfactory installation and operation of these encoding systems at Goldstone, they would serve, under JPL cognizance, as the Goldstone duplicate standard (GSDS) for stations in the World Wide Tracking Net.

Because Datex had achieved extremely high reliability in the earlier angular encoding systems and had been active in "electronic gearing" developments, the Datex Corporation was awarded the contract for the design, fabrication, and installation of the improved angular encoding systems. The Datex proposal was based on a JPL statement of work and specifications.

IV. FUNCTIONAL SPECIFICATIONS

The principal requirements for the angular encoding of each axis of both the receiving and the transmitting antenna are:

1. Angular displacement sensing is to take place at one end of each orthogonal axis (see Fig. 1 and 4).

2. Servo repeaters are to link the sensors (synchro resolvers) with the encoding disk assemblies. As much "electronic gearing" as off-the-shelf electromagnetic synchro resolvers will permit is to be incorporated, with the balance to be supplied by mechanical gearing.
3. Two encoding disk assemblies are to be employed, one for decimal (binary coded) and the other for binary representation.
4. Interrogation rate (readout command rate) will not exceed 1 interrogation per sec for the decimal channel and 1024 interrogations per sec for the binary channel.
5. The encoding logic shall be transistorized and angular data shall be available 150 microsec (or less) after an interrogation pulse (trailing edge) of 25 microsec (minimum) of duration.
6. Angular velocity about an antenna axis will not exceed 4 deg per sec. Angular acceleration about an antenna axis will not exceed 5 deg per sec.
7. Overall static accuracy at count transitions shall be 20 sec of arc (rms) or better for both the decimal and binary representations. A design goal of 10 sec of arc rms, however, is to be maintained throughout the engineering phase.
8. A maximum count of 180,000 for the decimal channel and 262,144 (2^{18}) for the binary channel is to be provided.

9. Visual displays shall be provided for the decimal channel. (JPL later added lamp banks to monitor the binary channels.)

A complete set of design specifications appears in Appendix B.

V. DESCRIPTION OF ANGULAR ENCODING SYSTEMS

The heart of the angular encoding system (Fig. 8) is the fine-count decimal (binary-coded) and binary encoding disks and their associated coarse-count disks.

A. Decimal Encoding Disk Assembly

1. Fine-count disk. The fine-count disk generates 2000 code combinations per turn; therefore, when geared to the antenna, 90:1 step-up, 180, 000 code combinations result per antenna revolution about an axis. Brushes riding on segments sense combinations of conducting and nonconducting segments making up a unit-distance code (see Appendices A and C). Four identical code patterns consisting of 000 to 998 counts in increments of 2 counts (i.e., 500 distinct code combinations) are on the fine-count disk. Since the least significant decimal digit progresses by 2's, only five combinations (0, 2, 4, 6, 8) need be represented. This calls for a code group of three bits (where a conducting segment and a nonconducting segment represent a binary 1 and binary 0, respectively). The two higher significant digits progress by 1's and require a code group of four bits.

The three-bit code employed by Datex is tabulated as follows:

Decimal Number	Binary Coded Representation		
	A	B	C
0	1	0	0
2	1	1	0
4	0	1	0
6	0	1	1
8	0	0	1

The three-bit code is unit distance except from 8 to 0. This requires that the least significant digit must be in the reflected portion just prior to closure (i.e., it must cycle through an even number of five combination groups). When counting by 2's in a reflected decimal code, the least significant digit is 8's complemented when the next-higher-order decimal digit is odd.

Reflected decimal equivalents of decimal numbers progressing by 2's are given as follows:

Decimal	Reflected Decimal
00	00
02	02
04	04
06	06
08	0$\underline{8}$
10	18

Decimal	Reflected Decimal
12	16
14	14
16	12
18	10
20	20
⋮	⋮
28	28
30	38
⋮	⋮
38	30

To convert the least-significant digit from its reflected to true decimal value, two rules are applied.

1. The least significant digit is unchanged if the next-higher-order decimal digit is even.
2. The least significant digit is 8's complemented if the next-higher-order decimal digit is odd. Note that the 8's complement of each of the three-bit combinations is derived by interchanging the A and C bits.

The four-bit code adopted by Datex for representing the two higher significant digits of the fine-count disk (as well as all other decimal digits) is tabulated as follows:

Decimal Number	Binary-Coded Representation			
	A	B	C	D
0	1	0	0	0
1	1	1	0	0
2	0	1	0	0
3	0	1	1	0
4	0	0	1	0
5	0	0	1	1
6	0	1	1	1
7	0	1	0	1
8	1	1	0	1
9	1	0	0	1

The four-bit code is unit distance with unit-distance closure (9 to 0). It is also reflected since the A, B, and C bits from 5 to 9 are reflections of those from 4 to 0, and the upper half of the decade is distinguished from the lower half by the state of the D bit. The inversion of the D bit (1's complement) of each four-bit combination yields its 9's complement. As explained in Appendix C, the conversion from reflected decimal to true decimal involves 9's complementing (when the count progresses by 1's).

In both the three- and four-bit Datex codes, the combinations of all 0's and all 1's are forbidden (i.e., unused). By ruling out all 1's, Datex is able to reduce power supply requirements in the associated logic. The use of at least one binary 1 and one binary 0 in every combination serves as a trouble-shooting aid.

To illustrate the unit-distance property of the code on the fine-count decimal disk, several successive counts along with their decimal equivalents are shown:

Decimal Number	Reflected Decimal Number	Actual Code Pattern
996	902	1001 1000 110
998	900	1001 1000 100
000	000	1000 1000 100
002	002	1000 1000 110

The count from 998 to 000 is the transition between patterns. Code combinations representing the successive reflected-decimal counts are separated by a unit distance. This reduces the count ambiguity in the region of count transition to ±1 count (see Appendix C).

2. Coarse-count disks. For one rotation of the antenna about an encoded axis, the respective fine-count disk makes 90 revolutions, and 90 times 4 or 360 patterns are generated. Each pattern consists of a 000 to 998 decimal count by 2's. Coarse-count encoding disks are utilized to tally the patterns traversed. (Coarse and fine disk code combinations are sensed for parallel readout.) The first coarse-count disk is geared 36:1 step-up to the antenna. It has one pattern and generates 36 patterns for one rotation of the antenna. Each pattern of the first coarse-count disk keeps track of 10 patterns of the fine-count disk, and therefore consists of a 0 to 9 decimal count or 10 counts by 1's.

The second coarse-count disk is geared 1:1 to the antenna axis. The 36 patterns associated with the first coarse-count disk (per antenna rotation) are counted by a single pattern on the second coarse-count disk. The pattern consists of a 0 to 35 decimal count by 1's.

The following table summarizes the correspondence between disk patterns:

Disk	Number of Code Patterns	Revolutions of Disk[2]	Patterns Generated[2]	Decimal Count	Count Increment
Fine	4	90	360	000-998	2
1st Coarse	1	36	36	0-9	1
2nd Coarse	1	1	1	00-35	1

The output of each disk represents three distinct though related numbers. The numbers are in a reflected decimal system. In the case of the first coarse disk's output, only a single decimal digit is represented. Therefore, the true decimal and the reflected decimal are equivalent since a single digit is necessarily the highest significant digit (see Appendix C). The output representation of the decimal encoding disk assembly varies from 000000 to 359998 in increments of 000002. This is actually a decimal degree representation of the antenna's angular position about one axis. The decimal is fixed and not part of the output. The least count is 000.002 deg, and the individual disk's contribution is shown for the representation of 359.998 deg.

[2]Per rotation of the antenna about an encoded axis.

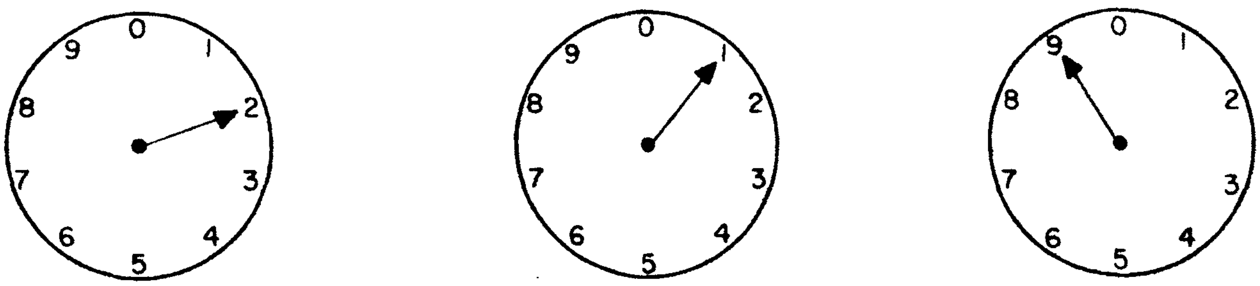
(359.998)

35	9	998	decimal degrees
↑	↑	↑	
34	9	900	disk assembly presentation (in reflected decimal)
2nd Coarse	1st Coarse	Fine	

For all decimal degree representations, the two highest significant digits are supplied by the second coarse-count disk, the third highest by the first coarse-count disk and the three least significant digits by the fine-count disk.

The coarse-count disks are mechanically geared down from the fine-count disk as shown in the functional block diagram in Fig. 8. The gearing accuracy requirements are much less severe than those between the antenna and fine-count disk; this is due to a double disk arrangement (for both the first and second coarse-count encoding). The next-higher-speed disk determines which of the two identical disks is read for a given antenna setting. The fine-count disk setting is used to select one of the two identical first coarse-count disks. In a like manner, the first coarse-count disk presentation determines the selection of one of two identical second coarse-count disks. Thus, the disk with the highest inherent resolution and accuracy (the fine-count disk) directly or indirectly (in the case of the second coarse-count disks) decides coarse-count disk selections. Each of the two identical disks is offset angularly an equivalent of 1/4 of its least count. One disk is advanced (the leading disk) and the other retired (the lagging disk).

As an aid to understanding the process of lead-lag disk selection and the resulting relaxation of gearing accuracy for coarse-count encoder's disks, consider the reading of a gas meter. In order to read the "tens" dial, the "units" reading must be considered; in order to read the "hundreds" dial, the "tens" reading must be considered.



A dial reading of 209 is arrived at by the following rules:

1. For next-lower-order nonweighted readings from 5 through 9, the nonweighted reading in question is less than the nearest apparent indication.

2. For next-lower-order nonweighted readings from 0 through 4, the nonweighted reading in question is greater than the nearest apparent indication.

The accuracy of the overall reading in the above example is dependent upon the accuracy of the units dial reading.

In the readout of the coarse decimal disks, lead-lag select is determined by logic according to the following set of rules:

1. For fine-count disk settings from 500 through 998 in decimal (590 through 900 in reflected decimal), the lagging first coarse-count disk is selected.

   For fine-count disk settings from 000 to 498 in decimal (000 through 490 in reflected decimal), the leading first coarse-count disk is selected.

2. For first coarse-count disk readouts from 5 through 9, the lagging second coarse-count disk is selected.

   For first coarse-count disk readouts from 0 through 4, the leading second coarse-count disk is selected.

Referring to the Datex four-bit code, the state of the D bit discloses whether a decimal digit representation is between 0 and 4 or 5 and 9. The ±1/4 count offset for the lead-lag disks is optimum, and therefore allows a maximum tolerance in the gearing between disks. In practice, sufficient tolerance is available such that the gearing design is not critical (see Ref. 1, ch. 6, pp. 45-49, 60-64, and 68-69 for related discussions).

A photograph of the encoding disk assemblies presently in use at Goldstone appears in Fig. 9.

B. Binary Encoding Disk Assembly

1. Fine-count disk. The fine-count disk generates 2048 (2^{11}) counts in reflected binary (Appendix C). The count increment is 0001. By gearing the fine-count disk to the antenna 1:128 (2^7), a 262, 144 (2^{18}) count in increments of 1 count results per antenna rotation about an encoded axis. This represents the binary count

nearest to (and higher than) the 180,000 total decimal count. By resolving one rotation of the antenna into a binary count, the coordinate converter which operates in binary is not required to make base conversions.

Unit-distant closure is realized on the fine-count disk since the total number of combinations is an integral power of 2. The reflected binary equivalent of 2047 (highest count) is 10000000000 and a unit-distance from the all-zero combination (lowest count).

2. Coarse-count disks. Two identical coarse-count disks comprising a lead-lag set are geared 1:1 to the antenna. A 128-count pattern of 1-count increments is on the coarse-count disks to tally the number of revolutions made by the fine-count disk. In effect, the 2^{11} (weighted) bit through the 2^{17} bit in true binary are supplied by the coarse disks. The 2^{0} bit through the 2^{10} bit in true binary are derived by the fine-count disk. Unlike the decimal disks, which all have reflected codes, the fine-count disk code pattern is reflected binary whereas the coarse-count disk code patterns are true binary.

The ambiguity in the region of coarse-count transition (described in Appendix C) is removed by the lead-lag selection of the coarse disks. One disk is advanced (leading) and the other is retired (lagging) just as in the case of coarse decimal (binary-coded) disks. The optimum angular offset is ±1/4 of the coarse disks' least count (Ref. 1). The true binary patterns provide a nonambiguous binary readout when disk selection is made according to the following rules:

1. When the next-lower-order bit (i.e., the highest significant bit of the fine-count disk) is a binary 1, the lagging coarse-count disk is selected.

2. When the next-lower-order bit is a binary 0, the leading coarse-count disk is selected.

These rules are essentially the same as those applied to coarse-decimal-disk selection. The binary 1 is analogous to the higher half-decade (5 through 9) while the binary 0 is analogous to the lower half-decade (0 through 4).

An example of a binary readout of the binary-encoding disk assembly is shown for a 102, 374-count representation.

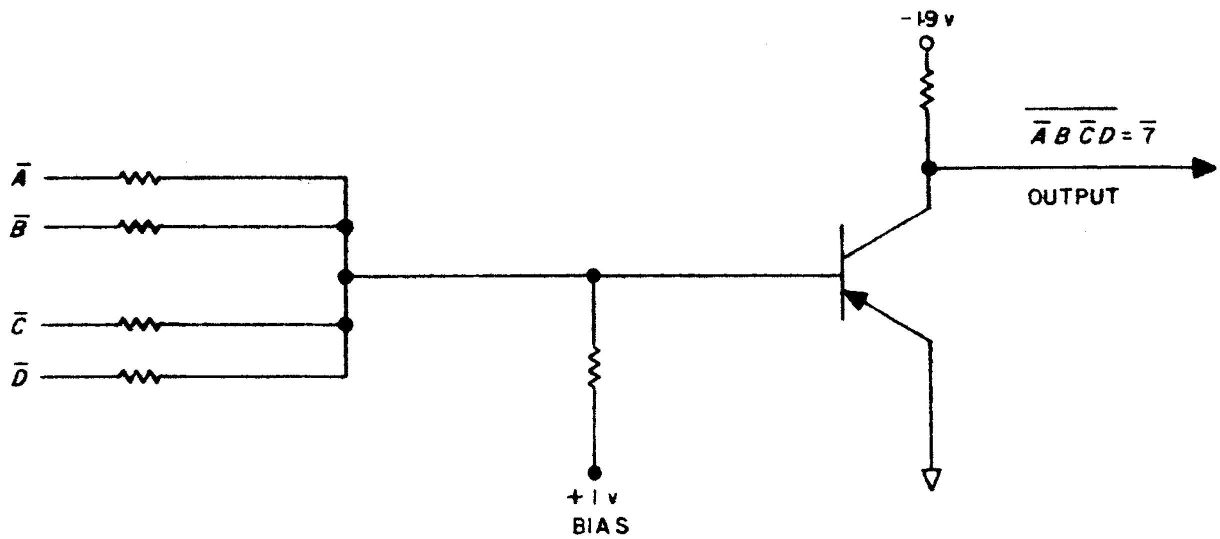
$102,374_{10}$		Count
$2^{17}.....2^{11}$	$2^{10}.......2^{0}$	binary weights
0110001	1111100110	true binary
0110001	1000010101	actual representation
coarse count in true binary	fine count in reflected binary	

C. Decimal Encoding Logic

Figure 10 schematically depicts the transistorized logic associated with the encoding of a decimal digit. By including portions or all of the logic circuitry, the derivation of an 8-4-2-1 binary-coded decimal representation of any but the least significant digit can be traced from its respective disk. The principles and basic circuit modules also apply for the least significant digit.

Suppose the brushes associated with the highest significant digit on the fine-count decimal disk are connected to the input (extreme left) of the logic. The odd-even sensing circuit (required for 9's complementing) is not used for the highest significant digit. The store-follow circuitry is comprised of a store-follow toggle (flip-flop) and four data transistor pairs. The bistable states of the store-follow toggle are determined by the level of the interrogation line. During the presence of a negative interrogation pulse, the left transistor is saturated and the right transistor is cut off, causing each of the four data transistor pairs to behave as two cascaded power amplifiers. A brush riding on a conducting segment (binary 1) is at ground potential, causing its left data transistor to be cut off (collector negative) and the right data transistor to saturate (collector ground). The reverse is true when the brush is riding on a nonconducting segment, thus having a negative potential. During the interrogation pulse, the data transistor pairs sense segment changes as described above. Upon the removal of the interrogation pulse (grounding of interrogation line), the store-follow toggle changes state to cause the data transistor pairs to remain in the states they were in just prior to the removal of the interrogation pulse. The absence of the interrogation pulse (store mode) also causes the data transistor pairs to ignore input changes. The store-follow circuitry thus enables encoding disk code-combinations to be sensed "on the fly." Readout in BCD is delayed for a minimum of 150 microsec after interrogation to permit switching transients to settle. This is not a severe restriction since the angular rate about any of the encoded axes cannot exceed 4 deg/sec. Therefore, the angular change between interrogation and readout cannot exceed 4deg/sec $\times$ 150 $\times$ 10^{-6} sec = 0.0006 deg, which is outside the 0.002 deg decimal-system resolution.

One of two outputs of each data transistor pair is fed to each of ten transistors for Datex code-to-decimal conversion. The circuit configuration forms a "not-and" (Ref. 9, 10) or Sheffer stroke type of logic. The four inputs are "anded" and negated (Ref. 9, 11) as follows:



Any one of the four inputs at a negative potential results in base current flow and saturation such that the collector (output) is grounded. When all four inputs are at ground potential the collector voltage and output are negative.

With reference to the brush lines, assume that the Datex code $\bar{A}B\bar{C}D$ (a decimal 7) is sensed. Only one transistor in the Datex code-to-decimal converter has all its inputs at ground potential. The output of this transistor (seventh from the top) is negative, and represents $\bar{7}$ (not seven) and feeds an inverter of the decimal lampbank driver. A negative input saturates the transistor and grounds the collector such that a return is provided for decimal 7 lamp. The $\bar{7}$ is thus logically negated to give 7 for display purposes.

The outputs of all the other transistors in the Datex code-to-decimal converter are at ground potential. The inverters in the decimal lampbank driver fed by these outputs are cut off such that their collectors are returned to ground through a high impedance, preventing the "turning on" of their respective lamps.

All the outputs of the Datex code-to-decimal converter are also fed to the decimal-to-BCD converter. The four channels in this converter provide the $2^3, 2^2, 2^1, 2^0$ or the 8-4-2-1 weighting for the BCD output. By examining the BCD equivalents of the decimal digits from 1 to 9, the required combinations of inputs for proper weighting become apparent:

Decimal Digit	Binary-Coded Decimal
	8 4 2 1
0	0 0 0 0
1	0 0 0 1
2	0 0 1 0
3	0 0 1 1
4	0 1 0 0
5	0 1 0 1
6	0 1 1 0
7	0 1 1 1
8	1 0 0 0
9	1 0 0 1

Those decimal digits whose BCD representation contains a binary 1 in a particular column are correlated as follows with the weight of that column:

Column Weight	Decimal Digits
1	1, 3, 5, 7, 9
2	2, 3, 6, 7
4	4, 5, 6, 7
8	8, 9

The 10 by 4-line matrix (i.e., decimal-to-BCD converter) has the decimal line grouping into the BCD lines in accordance with the latter tabulation. All inputs to the "not-and" logical transistor circuits must be at ground potential for a negative collector output. For any one of the inputs at a negative level, the collector or output is at ground potential.

In the example, all but the 7 line is at ground potential. The negative 7 line causes the outputs of the transistors (in the Sheffer stroke circuits) associated with the 1, 2, and 4 (weights 2^0, 2^1 and 2^2) lines to be at zero or ground potential. The corresponding transistor in the 8 (2^3) line has both inputs (decimal 8 and 9) at ground; therefore, its output is negative. Having defined ground as a binary 1 and a negative potential as a binary 0, the above outputs can be interpreted as a 0111 or the BCD representation of the decimal digit 7.

The JPL specifications in Appendix B called for two sets of logical levels:

Binary Representation	Nominal Voltage Level	
True (1)	-6 v	-13 v
False (0)	0 v	-23 v

The inverters in the output of the decimal-to-BCD converter provide the -6-v (binary 1) and 0-v (binary 0) set of levels. The final set of transistors provides inversion and level changing to satisfy the output requirement of -13-v (binary 1) and -23-v (binary 0).

In the encoding logic for the second highest significant digit of the fine-count disk, 9's complementing is required when the highest significant digit is odd. The D bit for the second highest significant digit, designated as D_0, is fed into the odd-even sensing circuit. The fictitious switch (SW) would be in the up position.

The D_0 bit is to be inverted when the highest significant digit is odd. The logic required can be determined from examining a table of combinations (Ref. 11) or truth table (Ref. 9).

Highest-Order Decimal Digit	Odd-Even Binary Representation (W)	D_0	New D
0	0	0	0
1	1	0	1
2	0	0	0
3	1	0	1
4	0	0	0
5	1	1	0
6	0	1	1
7	1	1	0
8	0	1	1
9	1	1	0

The D_0 column gives the state of the D bit of the second highest significant digit of a reflected decimal number for decimal digits 0 through 9 (in Datex code). An inversion of D_0 is required (9's complementing in Datex code) when the next-higher-order decimal digit is odd. By the use of a Karaugh map (Ref. 11) or a Veitch diagram or other minimization methods (Ref. 9, 11) a logical expression which is unique and has a minimum sum (redundancies removed) can be derived (Ref. 11). Designating the second column as W, the desired logical expression is

$$(\text{New})\ D = W\bar{D}_0 + \bar{W}D_0$$

This logical expression (Boolean function) is known as an "exclusive or" or "half adder" (binary addition without carry) function. Other designations such as "sum modulo two," "disjunctive sum," or "ring sum" (Ref. 11) are used. The function is often written $W \oplus D_0 = W\bar{D}_0 + \bar{W}D_0$. The expression implies that if W or D_0, but not both, are true, a binary true (1) results. The simple "inclusive or" function differs in that in a binary true (1) results if both are true.

The odd-even sense circuitry designed by Datex effects the 9's complementing decision in the following manner: The input to odd-even sensing is a diode (inclusive) "or" configuration connected to the even decimal line outputs (associated with the next highest significant digit) of the 4-by-10 matrix (Datex code-to-decimal converter). The "or'd" input is inverted and then "exclusive or'd" with the D bit of the second highest significant digit pattern on the fine-count disk designated as D_0. The exclusive "or" output is inverted and becomes the (new) D input to the data transistor pairs. Assume that the second highest significant digit in the reflected decimal code is 5, so that D_0 is at ground potential and represents a binary 1. Using 7 again as the highest significant digit, the "or'd" input lines will all be at ground, resulting in a negative voltage or binary 0 to be "exclusive or'd" with D_0, a binary 1. The output before inversion is at ground (binary 1). The final inversion results in a negative input to the (new) D line of the data transistor pairs; this represents a binary 0 or an inversion of D_0. Since the highest significant digit is odd, inversion of D_0 or 9's complementing correctly results.

For coarse-disk encoding logic, lead-lag selection circuits are used. The lag and lead transistor circuits are interconnected to form a lead-lag toggle. The D bit of the next-lower-order digit (which is the highest significant digit of the next-lower encoding disk) determines the bistable state of the lead-lag toggle. When a binary 1 (ground) appears at the toggle input, the lag transistor saturates and the lead transistor is cut off. Therefore, the lag common is at ground, providing brushes on the lagging disk a ground return when on a conducting segment. The lead common is returned to a negative potential sufficient in magnitude to back-bias the diodes in series with leading brushes when the leading brushes are on a conducting segment. The diodes in the lead-lag selection circuits serve to isolate the coarse lead-lag disks. In the foregoing example, the data transistor pairs sense the code combinations of the lagging disk. A binary 0 (negative) input to the lead-lag toggle causes the code combinations of the leading disk to be sensed.

One of the two BCD outputs is fed to data handling equipment, where it is serialized and converted to teletype code. Each six-decimal-digit angle is time-tagged along with other data to be transmitted over teletype lines.

A photograph of the decimal encoding logic (circuit modules) and the decimal lampbank (visual display) appears in Fig. 11.

D. Binary Logic

Many of the same circuit modules are used in both decimal and binary encoding logic. The store-follow control, lead-lag select and "exclusive or" circuits are employed in the binary channel (Fig. 12). The purpose and theory of operation of the store-follow circuits (to be explained in more detail) are identical to those used in the decimal logic. Conversion of the reflected binary pattern on the fine-count binary disk to a binary representation is done by means of "exclusive or" circuits.

In Appendix C, rules for conversion of reflected binary to binary are given. By "exclusive or-ing" a particular reflected binary digit with the next-higher-order binary digit, the corresponding binary digit is derived. The conversion is serial and takes place from the highest significant digit (in binary) to the lowest. At the outset, only the highest significant binary digit is known (identical to its corresponding reflected binary digit). It is used to determine the second highest significant binary digit, etc.

The input to the fine-count store-follow circuitry is reflected-binary. The brush leads are ordered from 0 through 10. These leads are not to be associated with weights, since reflected codes are not fixed-weighted. A negative or ground potential appears at each of the ordered inputs and corresponds to a binary 0 (non-conducting segment) or binary 1 (conducting segment), respectively. The output is taken from the collector of the transistor of the data transistor pair which reverses the above correspondence to satisfy the specified, nominal output, logical levels of:

-6 volts for binary 1

0 volts for binary 0

The role of the logical circuits is discussed without further reference to the logical levels.

The reflected-binary-to-binary conversion resulting in the 2^{10} through 2^0 weighted bits is illustrated by example.

10	9	.	.	.	.	.	.	.	.	0	brush order
1	0	1	1	0	1	1	1	0	0	1	reflected binary
1	1	0	1	1	0	1	0	0	0	1	binary
2^{10}	2^9	.	.	.	.	.	.	.	.	2^0	binary weights

Those binary digits joined by arrows are "exclusive or'd" to determine the next-lower binary digit. By applying the rules presented in Appendix C, the following table of combinations can be derived;

n Bit Binary	n-1 Bit Reflected Binary	n-1 Bit Binary
0	0	0
0	1	1
1	0	1
1	1	0

This, in fact, corresponds to "exclusive or" logic.

Lead-lag selection of the coarse-count disk is identical to that described in the decimal case. The 2^{10} bit (binary 1 or binary 0) determines coarse-disk selection (lagging or leading). The coarse-count store-follow input circuitry provides diodes for isolating the coarse disks.

The store-follow circuit modules (used in both decimal and binary logic) contain either lead-lag isolation diodes or integrator circuits in the inputs. The integrators, each of which is comprised of a 7-volt zener diode, a capacitor, and two resistors (through one of which brush current flows), are used to filter spurious noise from high-speed (fine-count) disks when readout speeds in excess of 30 rpm may be required. As stated previously, the slow-speed (coarse-count) disks require diode inputs for lead-lag disk isolation.

Binary readout "on the fly" does not (as in the decimal channel) introduce appreciable angular readout error at the maximum antenna angular rates.

Lampbank driver boards (two per binary channel) were added after installation to the binary outputs. Eighteen inverter amplifiers (one per bit) were used to monitor each binary channel. A binary 1 (-6 v) is indicated if the lamp in the collector circuit is on. A binary 0 (0 v) is indicated if the lamp is off. The lamps are grouped by threes such that an octal presentation is available for the observer.

Figures 1 and 4 show the decimal and binary encoding logic and visual displays installed. The sizes of the racks and equipment are exaggerated for emphasis.

E. Sensors and Servo Repeater

The sensors of antenna rotation (transmitting synchro resolvers) are part of a servo repeater that provides the precision electromechanical gearing required by the decimal and binary fine-count disks. These elements (see Fig. 8) are described below:

A multipoled synchro resolver plays the most important role in providing accurate gearing. The multipole resolver was designed and developed by Bell Technical Laboratories; Clifton Precision Products Company is licensed to manufacture them. The performance characteristics are similar to those of a geared-up synchro resolver. The resultant of the two resolved electrical signals rotates through an angle that is a multiple of the mechanical (input) shaft rotation. In the case of the multipoled resolver, the step-up is derived electrically.

The multipoled synchro resolver has two distinct advantages. Laminations of the rotor and stator give rise to a statistical averaging effect (Ref. 12), thus reducing the required machining accuracy far below the accuracy realization of the end product. Brushes and slip rings are eliminated, since all windings are on the stator. The elimination of the brushes and slip rings found in conventional synchro resolvers adds to ruggedness and reliability. Inaccuracies in machining laminations are reduced, since the orientation of each lamination is averaged in the electromagnetic induction process.

The multipoled synchro resolver, like conventional synchro resolvers, may be classed as a variable coupling transformer. A fundamental difference is the variation of induced voltage which is due to the variation in the reluctance of the magnetic paths between the exciting and sine-cosine windings. The reluctance of the magnetic path for the excitation flux is varied almost sinusoidally by rotating the rotor, which has equally spaced serrations or teeth on the periphery of the rotor laminations.

The magnitudes of the sine and cosine winding outputs vary sinusoidally with the electrical angular change and are a multiple of the mechanical (input) angular change. The number of teeth on the rotor determines the order or ratio of electrical angular change to mechanical angular change of a given multipoled resolver. At the time the design of the encoding systems was initiated, "off the shelf" multipoled resolvers with an order of 27 were available. Though higher-order laboratory models had been fabricated and tested, production units were not then available.

The accuracy and repeatability of individual multipoled resolvers were not experimentally checked because of the stringent fabrication and test time schedules. However, each channel of the encoding systems now in operation was carefully put through overall accuracy tests (see Sect. VI). The specified accuracy of 20 sec of arc (rms) referred to the encoded axis was met for each channel. The above measurement was made with compensation introduced for repeatable errors (to be discussed later). The output of each multipoled resolver proved to have repeatable errors. (See Ref. 12 for a discussion of harmonic content.) This indicates that each multipoled resolver with repeatable error compensation necessarily had an accuracy of better than 20 sec of arc rms referred to its input shaft. Repeatability for each of the channels (for desired readings approached with input rotations of the multipoled resolvers taking place in the same direction) was measured to be 4 sec of arc or better. Repeatability of the resolvers must therefore be at least as good as 4 sec of arc.

The sine and cosine outputs are compared with the sine and cosine outputs of a conventional single-poled resolver. The difference represents an error signal and is fed to a transistorized amplifier via the coarse-fine synchro switch. (Note that the multipoled resolver is also termed a vernier or fine resolver.) The control winding of an ac servo motor serves as a load to the servo amplifier whose output is either in phase or in phase opposition with the excitation voltage of the servo motor's reference winding. The direction or sign of the error determines the phase relationship between the control and reference voltage and, hence, the direction of rotation of the servo motor. Geared to the servo motor is the single-poled resolver, whose output is to be compared with that of the multipoled resolver. It is driven by the motor in such a direction that a near-zero error results whenever the input shaft of the multipoled resolver is rotated. The single-poled resolver rotates through an angle 27 times that of the multipoled resolver's input shaft. When the input shaft is fixed, the error is nulled such that the control voltage reduces to zero and the servo motor ceases to rotate. Inertial damping proportional to the angular acceleration of the servo's output aids in stabilizing the servo repeater. The only feedback is positional, making the servo a type 1 or positional servo (Ref. 13).

The above discussion deals with the vernier servo loop, in which the multipoled synchro resolver (transmitter) serves as a sensor and comparator, with a single-pole resolver providing feedback proportional to the positional error of the 27-speed shaft.

Just as in the case for two-speed synchro resolvers used as sensors, ambiguity arises when closing the fine loop. There are 27 positions of the multipoled input shaft that could be nulled by a given angular setting of the single-poled resolver in the vernier loop. Some means must be incorporated to ensure that a particular 1:1 correspondence is maintained between the angular input settings of the multipoled resolver and the 27-speed shaft in the servo repeater. Rotation of the antenna during the removal of encoding system power, for example, could result in a change of the above correspondence when encoding system power is applied. The ambiguity of correspondence is resolved by coupling a single-poled synchro transmitting resolver to the encoded axis and having its output compared with that of a single-poled synchro receiving resolver geared down 27:1 from the 27-speed shaft in the servo repeater. Whenever the compared outputs of the 2 one-speed resolvers exceeds a preset threshold, the coarse-vernier transistorized synchro switch interprets this condition as a coarse error signal and delivers it to the servo amplifier. Coarse loop closure results until the error signal falls below the preset threshold level, which indicates that the input shaft to the multipoled resolver is in proper correspondence with the 27-speed shaft. The synchro switch then returns control to the multipoled resolver for vernier-loop servo operation. The error-signal threshold setting for coarse loop servo operation corresponds to a 2 to 3-deg angular error between the one-speed resolvers. Each pseudopole of the multipoled resolver is associated with a 13.3 deg mechanical angle (i.e., 360/27). The coarse loop thus provides enough coincidence to realize proper correspondence in the vernier loop. Normally, the sensors and servo repeater are operating in the vernier mode. A photograph of a multipoled and single-poled synchro resolver assembly now mounted on the HA-DEC antenna is shown in Fig. 13.

Within the servo loop, a 90:1 step-up drive is developed for the fine-count decimal disk. Mechanical gearing between the servo motor and the 27-speed shaft is such that a 90-speed drive is obtained and the motor is permitted to operate over rated speed ranges. Mechanical gearing of 10:3 step-up from the 27-speed shaft provides 27 x (10/3) or a 90:1 (referred to antenna rotation) step-up drive.

The velocity constant or error coefficient was determined experimentally by Datex for the case where the angular position of the 90-speed shaft (referred to the encoded axis) is considered to be the controlled variable. A Kv of 300 sec^{-1} was measured. This is the velocity of the controlled variable over the actuating error for a constant rate of change of the controlled variable (Ref. 13). The positional error of the 90-speed shaft for a nominally high tracking rate of 1 deg/sec would be

$$\frac{1° \ sec^{-1}}{300 \ sec^{-1}} \text{ or } 0.0033°$$

Mechanical gearing of 128 to 90 step-up from the 90-speed shaft provides the 128:1 (referred to antenna rotation) step-up drive.

A layout of all the mechanical gearing in the servo repeater appears in Fig. 14. To achieve the 20 sec of arc rms, overall system accuracy, the design of the precision mechanical gearing has been approached with care. The choice of available gears and bearings along with the machining of bearing housing bores is critical. Of paramount importance is the painstaking attention that must be given in assembling the gear train components.

Backlash and gear inaccuracy (Ref. 14) are two fundamental sources of positional errors arising in the transmission of motion and power in a gear train. Backlash can be described as lost motion between gears. It is the amount by which the width of a tooth space exceeds the thickness of the engaging tooth measured on the pitch circle (Ref. 14). Backlash gives rise to positional errors and can cause poor servo response and servo instability.

Sources and analyses of backlash appear in Ref. 14. The sources listed are:

1. Gear center-distance variation.
2. Gear size.

3. Pitch diameter runout.
4. Ball bearing errors.
5. Gear assembly to shaft.
6. Shaft runout.
7. Looseness of shaft, bearing and housing bore.
8. Composite gears.
9. Environmental sources.
10. Rigidity of installation.

As indicated in Fig. 14, Datex incorporated adjustable centers at various points in the gear train, enabling reduction of backlash caused by gear-center distance variation. Increases in assembly costs are justified by larger gear-center location tolerances and gear size tolerances. The adjustments are critical and should not be made in the field.

Inaccuracy independent of backlash is also present in gears and may be described as positional errors due to the variation of velocity ratio with meshed gear rotation. This inaccuracy, termed total composite error, results from the less than perfect methods of generating gear teeth. Even the employment of optical indexing when cutting gear teeth cannot completely eliminate the errors.

In Ref. 14, four basic types of inherent gear errors are listed and described as:

1. Pitch circle runout or pitch error, which is the eccentricity of the gear bore and the pitch circle.
2. Tooth thickness variation or spacing error, which is the variation of the circular pitch.

3. Profile error, which is the descrepancy between actual tooth form and the theoretical involute.

4. Lateral runout or wobble of the pitch plane, which causes indirect profile error and backlash.

In order to calculate the maximum and the probable gear train inaccuracy, a complete set of manufacturing specifications, a knowledge of manufacturing techniques and limitations, and an understanding of the interrelation of the gearing parameters (Ref. 14) are necessary. The maximum inaccuracy represents an extreme case in which each error is assumed to approach the limit specified by a respective tolerance. A more meaningful inaccuracy figure is the probable inaccuracy. This is the practical result of summing component probable errors. The maximum inaccuracy, though simple to calculate, has a low probability of occurrence in practice.

The reflected inertias constitute another very important consideration in the precision gear train design in the servo repeater. Since inertias are reflected by the square of the gear ratio, the total inertia reflected to the lower-speed shafts can be quite large (Ref. 1).

Figure 15 is a photograph of the servo repeater in which the precision gearing is located.

The repeatable errors in the gear train and multipoled resolver are compensated within limits. A compensation cam mounted on a single-speed shaft actuates a cam follower which is linked to the housing of an encoding disk assembly. The housing is rotated in accordance with its associated cam profile, and a relative displacement between the brushes and disks occurs such that predetermined counts are added or subtracted to reduce dominant repeatable errors. Cam profiles are determined experimentally for each cam and channel combination. Cables from the sensors on the antenna to the servo repeater influence the cam profiles, making cables of equal length noninterchangeable. Datex has since discovered that twisted pairs of conductor runs minimize mutual coupling between conductors to the extent that cable interchangeability is feasible. A pronounced 54-cycle variation in each cam profile can be attributed to the second harmonic output of the multipoled resolver.

Operation of the encoding system in the field revealed that the difference in the decimal and binary channel readings for each encoded axis varied appreciably from day to day. After an optical alignment of the antenna at its zenith pointing angle, the decimal and binary channels were indexed to agree with the optically measured angular displacement of the antenna about the respective encoded axis. Differences of hundredths of degrees between the decimal and binary channels would appear in subsequent checks at zenith settings. The difficulty was traced to restraining forces on the housing of each encoding disk which prevented the introduction of the desired repeatable error compensation. Conductors connected to the brushes mounted on the interior of the encoding disk housing are brought out of the servo repeater chassis through a chassis-mounted connector. The conductors, bundled to form a cable, did not have enough flexibility to permit housing rotation as an exact function of the cam profile. Also,the cam roller, mounted on a lever arm, was on a friction bearing; sliding instead of rolling resulted. The cable jacket was removed and the conductors were replaced with smaller-gaged, more flexible conductors to minimize the restraining forces. JPL also redesigned the cam rollers and mounted them on ball bearings to reduce wear and enhance their reliability. These changes substantially reduced the peak variation in the decimal and binary to less than 0.006 deg at the zenith setting. This variation is realistic when the additional mechanical gearing (which lessens accuracy) in the binary channel and the quantization and encoding disk errors in both channels are considered.

F. Mechanical Coupling of Sensors

The inaccuracy of the mechanical coupler between each encoded axis and multipoled resolver contributes to the overall encoding system inaccuracy. Any encoding technique is affected by coupling inaccuracies. For those systems designed for "state of the art" accuracy performance, mechanical coupling inaccuracy may be the limiting factor.

Angular positional changes must be transmitted by the mechanical coupler with a high degree of accuracy. Since, in practice, coupled shafts cannot be aligned perfectly, the coupler must accommodate expected radial, axial, and angular off-sets between the coupled shafts. Because of the low rates of antenna rotation, the coupling problem is essentially a static one. Couplers whose accuracies deteriorate with use are undesirable for maintenance reasons. In order that the coupler's inaccuracy be a negligible contribution to the overall encoding system inaccuracy, 2 sec of arc (rms) coupling accuracy was sought.

JPL specified miniature Thomas Flexible Couplers for all sensor-to-encoded-axis coupling. Discussions with the chief engineer at the Thomas Flexible Coupling Company revealed that the coupler of the required size could tolerate 2 deg of angular offset, ±0.040 in. of radial offset, and ±0.060 in. of axial offset between the two coupled shafts. The special design incorporating engaging clamps which yield a higher compliance than either a spline or set-screw engagement is used for each system. Data supplied to the Thomas Company by customers, although in some cases incomplete and questionable because of the test setup or technique of measurement, indicated that 5 sec of arc peak inaccuracy was a reasonable engineering figure. The Thomas flexible couplers in use at Goldstone are shown in Fig. 1, 4, 13, 16, and 17.

A precision test fixture has been designed at JPL for evaluating coupler accuracy by optical techniques. The machining of the test fixture is near completion; however, data are not available for the present report. Provisions for introducing known radial axial and angular offsets by means of micrometer screws and flexures are being built into the test fixture. Since each encoding system including the mechanical couplers satisfactorily passed overall accuracy tests, tests of individual mechanical coupler performance were given a secondary priority.

G. Encoding Count Sense

The direction of rotation of the encoding disks that results in an increasing count output is fixed by the patterns of the disks. For spares and interchangeability purposes, it was decided to have each system identical, including the pattern sense of each disk. Since the cam profile is largely determined by the repeatable errors in the multipoled resolver and the precision gear train, a reversal in encoding count sense cannot be made after cams have been cut and installed without severe accuracy degradation. Reversing the sense of the electrical output of the multipoled resolver or the sense of rotation of the servo motor's rotor destroys the correspondence of the cam profile with the multipoled resolver's repeatable errors.

The direction of increasing hour angle and declination for the receiving antenna and increasing azimuth and elevation for the transmitting antenna were established, thereby dictating the sense of the angular inputs to the coordinate converter (see Fig. 7 for assignment of the above senses). Only the north end of the polar axis and the low end of the azimuth readout axis were available for the sensors. A clockwise rotational drive at the input shaft of the multipoled resolver coupled to each of the above axes was required to cause an increasing encoded count output. It was decided to mount the sensors for the declination axis and the elevation axis at those ends which would result in the same increasing count sense. Compensating cams were cut for all the encoding systems, with clockwise inputs (to multipoled resolvers) representing increasing count outputs.

Only in the case of the elevation axis was any difficulty encountered. Power-servo personnel, who had believed that the zenith angle (complement of the elevation) would be encoded, installed the sensor housing at the incorrect end of the elevation axis. An increasing zenith angle corresponds to a decreasing elevation angle. To obtain the previously established elevation angle sense, the multipoled resolver was mounted on the elevation readout axis (see cutaway in Fig. 4) such that the resolver shaft remains stationary while the body of the resolver is rotated. This scheme effectively reverses the mechanical input drive. Other alternatives such as cutting new cams (which will be adopted as a long-range solution) or purchasing new encoding disk assemblies with reverse patterns were not adopted because of the time and cost involved.

VI. ENCODING SYSTEM ACCURACY TESTS

A precision test fixture was designed, machined, and assembled at JPL for accuracy tests of the encoding systems and the encoding disk assemblies. Machining and bearing tolerances are consistent with the desired absolute measuring accuracy of ±2 sec of arc. The test fixture pictured in Fig. 17, 18, and 19 consists of a rotating table whose angular position can be set very accurately. A spindle clamped to the table is dual-bearing-mounted and extends into a cylindrical housing as a shaft. An encoding disk assembly may be directly coupled to the shaft with the housing kept stationary by means of a spring-loaded torque bar which allows for radial play (i.e., shaft runout). With the addition of a mounting plate, a multipoled synchro resolver can be mounted and coupled to the spindle by means of a Thomas Flexible Coupler. The single-poled resolver is coupled to the multipoled resolver by means of a flexible coupler or one-to-one mechanical gearing. The actual sensor input drive may therefore be simulated.

A Wilde T-3 theodolite, which may be considered to be a precision transit, was used to measure spindle rotation. The Wilde T-3 is a direct reading device with no mechanical gearing. Optical techniques are used to provide the coarse and vernier indications. The angular rotation of the telescope about an azimuth and elevation axis is indicated to an absolute accuracy of ±1 sec of arc.

The T-3 was mounted on the table of the precision test fixture. As shown in Fig. 18, the entire assembly was placed on a rigidly mounted microflat table. Experienced personnel require approximately 2 to 4 hours to properly align the T-3 with the precision test fixture and a reference target. The azimuth axis of the T-3 is aligned as closely as practicable with the input shaft of the multipoled resolver (or a directly coupled encoded disk assembly). A zero-elevation locked setting of the T-3 is used throughout the test such that the optical axis of the telescope lies in a plane perpendicular to the azimuth axis. A fixed reference target is placed in line with the optical axis. The target and test assembly were separated by at least 30 ft for each accuracy test. Total indicated runout (TIR) or radial offset between the azimuth axis and spindle shaft was 0.001 in. Thus, the 30-ft distance ensures that the error introduced by the radial offset does not exceed 0.6 sec of arc.

In measuring an overall system channel accuracy, the resolvers are initially positioned for an all-zero count transition as indicated by the visual display. The telescope of the T-3 is positioned for a 0-deg reading, and the entire table is rotated (before the spindle shaft and resolvers are coupled) until the center of the target is sighted in the center of the reticle. The table is then held fixed by clamping a brake to a circular phosphor bronze wafer which normally rotates with the table; the resolvers are then coupled to the spindle shaft for the start of an accuracy run. The test procedure continues as follows:

1. The T-3 and table assembly are rotated throughout 360 deg to provide a minimum of 100 output counts (in equal increments) as indicated by the visual display.
2. After each count output is set at the transition from the next lower count to the count in question, only the telescope portion of the T-3 is returned to the reference target. This gives an optical measurement of the total angle through which the input shaft of the multipoled resolver was rotated to give a particular output

count transition. The number of readings and the increments can be chosen arbitrarily in this psuedocollimation scheme.

3. The difference between the output count transition and the angle of rotation indicated optically for each setting is recorded.

Error information determined in step 3 does not include inherent quantization errors. The measurements are therefore confined to those inaccuracies which are theoretically removeable. The advantage of count transition measurements lies in the ability to repeat particular measurements for checking purposes and repeatability determination. Since transition regions are small fractions of a sec of arc, coarse- and fine-vernier controls for table rotation were incorporated into the test fixture. All readings are approached from the same direction. Having positioned the table to within several counts below the desired count transition, the brake described above is applied. Rotating the coarse- or fine-vernier control causes the brake to move in a peripheral direction (with reference to the circular wafer). The circular wafer, and hence the table, is rotated by brake motion. Two lever arms with phosphor bronze flexures used as fulcrums actuate the brake assembly (mounted on flexures). The lever arms reduce the longitudinal motion of the fine-vernier knob by the ratio of 1:196. Rotation of the fine-vernier knob actuates a lever arm on which is located (near the fulcrum) the coarse-vernier screw which is always in contact with another identical lever arm. The second arm is actuated either by the first lever or by rotating the coarse-vernier knob. The brake assembly is mounted near the fulcrum of the second lever. Its peripheral motion (see Fig. 19) is 1/14 times the longitudinal motion of the coarse-vernier knob or 1:196 times the longitudinal motion of the fine-vernier knob. The peripheral motion of the spindle shaft is a fraction of the brake assembly's peripheral motion. One rotation of the coarse-vernier knob results in a table rotation of 49 sec of arc. One rotation of the fine-vernier knob causes 3.5 sec of arc of table rotation. The equivalent decimal and binary channel quanta are tabulated below:

One Rotation of Vernier Knob	Table Rotation, sec	Decimal Quanta	Binary Quanta
Coarse	49	6.8	9.9
Fine	3.5	0.49	0.71

The measurements recorded in step 3 of the test procedure are used to calculate the sample mean and rms about the mean as expressed as follows (Ref. 15, 16):

$$X^* = \frac{1}{n} \sum_{k=1}^{n} (X_{k_s} - X_k)$$

$$S^* = \sqrt{\frac{1}{n} \sum_{k=1}^{n} \left[X^* - (X_{k_s} - X_k) \right]^2}$$

where, as defined in Section III-D,

X_{k_s} = kth reading of the angle represented by the encoder count output (at count transition)

X_k = kth reading of the angular position of the input shaft of the multipoled synchro resolver as measured by the Wilde T-3 theodolite

X^* = the sample mean error

S^* = the rms error about the sample mean error

n = the total number of readings (100 or greater)

The sample mean error is the value of encoding error about which the test measurements tend to cluster. It represents a system bias which can be removed by reindexing the channel's encoding disk assembly. The rms error, termed standard deviation in statistics (Ref. 17), is a measure of the dispersion of the encoding errors about the sample mean error.

Accuracy test data for the decimal and binary channels of the elevation encoding system now in operation at Goldstone are tabulated in Tables 1 and 2. The count transition increments ΔX_k were chosen as (the equivalent of) 3.602 deg in the decimal channels and 2,601 counts (in binary) for the binary channels. With these increments, the counts on the fine-count decimal and binary disks are never repeated in the 90 and 128 revolutions, respectively, associated with 360 deg of rotation of the input shaft of the multipoled resolver. The significance of the digits in the error, $X_{k_s} - X_k$, are never greater than those emanating from the fine-counts disks. Thus the standardized data runs are valid for even those systems encoding an axis about which incomplete antenna rotations are made.

The distribution of errors can be illustrated by histograms for which geometric interpretations of sample mean and rms error are apparent. The number of observations (i.e., error measurements) falling within a particular interval termed class interval are plotted for the elevation decimal and binary channels and the azimuth decimal and binary channels in Fig. 20. The length of the class interval was selected as 0.002 deg for the decimal and the binary channels. The number of observations, y, that fall within the jth-class interval satisfies the inequality (Ref. 16):

$$t_j - \frac{\Delta t_j}{2} < y \leq t_j + \frac{\Delta t_j}{2}$$

where

t_j = jth class interval

t_j = midpoint of the jth-class interval

By dividing the number of observations by the total number of readings, the frequency of observations (Ref. 16) in a particular interval can be determined. The centroid or the first moment about the origin measured along the abscissa of error-distribution histograms is the sample mean; the second moment about the mean is a measure of sample variance (Ref. 17) S^{2*}. Its square root S^* gives an indication of the dispersion of errors about the mean. As stated previously, this is the rms accuracy or standard deviation. For the commonly encountered normal or gaussian distribution (Ref. 15-17) the interval from $X^* - S^*$ to $X^* + S^*$ will include approximately 68% of all the observations. The quantities X^* and S^* converge in probability (Ref. 15) to μ, the mean, and σ, the standard deviation, encountered in probability theory. The normal probability density function is completely determined by μ and σ. The values of X^* and S^* can be used as maximum likelihood estimates of μ and σ, respectively, for fitting a normal distribution curve to the statistical data. An χ^2 test can be used to apply a quantitative measure to the goodness of the fit (Ref. 16, 17).

In the histograms showing error distribution, the ratio of the area (under the curve, i.e., the bars) falling within the ±rms values on the abscissa (intervals of error) ɪdication of the probability of errors falling within the ±rms ɔding system channel, over 65% of the observations fell within alue, which indicates that the dispersions are similar to or more ɔse of normal distributions having the same respective mean and 1 deviation).

to providing desired rms error information, laboratory accuracy : following:

1. The undesirable varied influence of cables between sensors and servo repeaters on repeatable system errors making these cables noninterchangeable (see Section V).
2. The problems posed by nonintegral gear trains in the servo repeaters.
3. The negligible contribution to system errors made by inaccuracies of encoding disk assemblies.
4. The repeatability of each encoding system channel.

'or each rotation of the input shaft of the multipoled resolver, each gear in ɔciated servo repeater does not make an integral number of revolutions. The ·ains are said to be nonintegral and present two problems. First, the cam ənsation is valid for only the gear train cycle for which the cam profile was :mined, which requires careful mechanical indexing of the multipoled resolver, r train, and decimal and binary cams. Secondly, the mechanical limits of the .nsmitter antenna axis is such that a ±540 deg of rotation is permitted. Since the ·ofile of the compensation cam is associated with a particular gear-train cycle, legradation of azimuth encoding accuracy is to be expected. By extending the accuracy run for the above, it was discovered that the 20 sec of arc rms accuracy is met for approximately 540 deg or ±270 deg of input. Figure 21 is a plot of error distribution of the azimuth binary channel for 151 readings or approximately 540 deg of encoded axis rotation. Comparing this with 101 readings (360 deg), the rms accuracy falls from 0.004 to 0.005 deg. A sharp deterioration of accuracy was noted for readings beyond 151. This deterioration does not present a serious problem in practice, since the multipoled resolver can be reindexed with respect to the azimuth readout shaft for tracking requirements outside the desired ±270-deg region. However, it was important to be aware of this accuracy limitation.

Tests performed for encoding systems were repeated for encoding disk assemblies alone. Measurements in system tests were repeated for the disk assemblies assuming ideal coupling and ideal gearing with the encoded axis such that:

$X_k = 90/X_{ke}$ for decimal encoding

$X_k = 90/X_{ke}$ for binary encoding

where X_{ke} = kth reading of the angular position of the input shaft of the encoder disk assembly.

Histograms in Fig. 22 show the error frequency distributions of a decimal and binary encoding disk assembly referred to the encoded axis. These two disk assemblies represent the relatively least-accurate decimal and binary disk assemblies tested. In comparing their accuracies with those of each of the respective decimal and binary system channels (listed below), their error contribution can be neglected, thus indicating that the encoding disk assemblies can be reindexed with respect to their input drive shaft and interchanged without any appreciable change in system accuracy. Therefore, indexing fixtures were designed and machined at JPL to enable the relative angular position of each set of disks and its respective input shaft to be varied. An indexing fixture (Fig. 23) is installed at the mechanical input of each disk assembly. To achieve indexing down to least-count angles, the fixture must be capable of providing angular changes as small as 0.002 deg x 90 = 0.18 deg for decimal, and 0.00137 deg x 128 = 0.175 deg for binary.

After each optical alignment of the antennas, the disk assemblies are reindexed where necessary to correspond to zenith pointing angles determined optically. Variations in the antenna structure account for changes in the encoded zenith angles.

Repeatability of each channel was measured in the laboratory to be 4 sec of arc or better when readings were approached from the same direction to eliminate effects of backlash.

The results of laboratory accuracy tests (static) of the systems now in operation are summarized as follows:

	S*, deg	
Encoded Axis	Decimal Channel	Binary Channel
Hour angle	0.0037	0.0052
Declination	0.0040	0.0047
Azimuth	0.0042	0.0051 (540 deg)
Elevation	0.0026	0.0050

VII. AUXILIARY TEST EQUIPMENT

A. Encoding Test Units

Decimal and binary test units were designed and fabricated at JPL to aid in indexing, servicing, and testing the decimal and binary channels. The test unit senses the code combination in an associated encoding disk assembly and serves to provide any of the following separately:

1. Presentation of the actual encoding disk code combination on a lampbank display (on = binary digit 1; off = binary 0).
2. Presentation of the code combination after conversion by relay logic from a reflected to a natural code is also presented on the lampbank display. The decimal presentation is in the Datex code. The binary presentation is grouped by threes for octal representation.
3. Information for properly phasing the coarse-count disks.
4. Information for locating subunit faults. Since the test unit logic essentially duplicates the transistorized encoding logic, it can serve to help locate circuit and component failures.

B. Decimal Encoding Channel Test Unit

The decimal test unit is shown in Fig. 24. Not shown are the input and output connectors mounted on the rear of the test unit. The decimal encoding disk assembly is cabled to the input of the test unit. The output of the test unit is cabled to the transistorized decimal logic when the entire channel is under test. The front panel controls are:

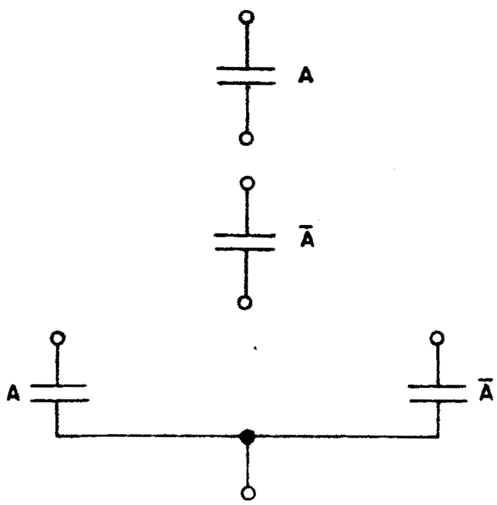
1. Ac power on-off, toggle switch.
2. Test-operate, toggle switch.
3. Decimal degree (presentation), disk pattern, lever switch.
4. Coarse-disk indexing, toggle switch.

With the test-operate switch in the "test" position and ac power on, the test unit's circuitry is connected to the encoding disks' brushes. In the "operate" position, the test unit's circuitry is bypassed, and the encoding disks' output is fed directly through the test unit to the transistorized logic. The test unit in this case is equivalent to a short run of cable. Having determined the encoding disks' setting (test), the disks' output is passed on to the transistorized logic (operate). The test unit's presentation is compared with that of the transistorized logic, thus aiding in fault location (i. e., in disk assembly or transistorized logic).

For the remainder of the discussion, it is assumed that the "test-operate" switch is in the "test" position with ac power on.

Controls 3 and 4 are spring-loaded such that the true decimal degree setting is normally displayed by the lamps in Datex code. A self-contained power supply provides power for the relays (logic) and lamps. By depressing the lever switch, the relay logic is removed from the test unit circuitry, and the actual disk pattern is displayed. By holding the coarse-disk indexing switch in the up position, the phasing of the two sets of coarse disks can be checked or adjusted (as will be explained later in this section).

A schematic diagram of the decimal encoding channel test unit appears in Fig. 25. The derivation of logical expressions with minimization techniques employed and their implementation with relay logic will be examined. The schematic symbol in Fig. 25 for relay contacts was chosen to aid in wiring the relay circuits. However, in logic diagrams, the following symbols (Ref. 11) are used for simplicity.



contacts normally[3] open

contacts normally closed

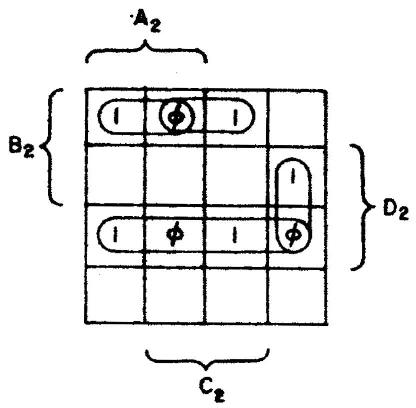
transfer contacts

Referring to Section VA, the least-significant decimal digit is 8's complemented when the A and C bits of the three-bit Datex code are interchanged. For odd next-higher-order decimal digits, the least-significant digit is 8's complemented. The table of combinations (truth table) satisfying the required logic is shown below:

2nd-Least-Significant Digit					8's Complement Required
Decimal	Datex Code				(1 - true, 0 - false)
	A_2	B_2	C_2	D_2	
0	1	0	0	0	0
1	1	1	0	0	1
2	0	1	0	0	0
3	0	1	1	0	1
4	0	0	1	0	0
5	0	0	1	1	1
6	0	1	1	1	0
7	0	1	0	1	1
8	1	1	0	1	0
9	1	0	0	1	1

[3] Relay coil is de-energized.

Plotting the table of combinations on a Veitch diagram (Ref. 9) for minimization of the standard sum form (Ref. 11) gives:



ϕ represents optional states (forbidden combinations) used to enhance simplification (Ref. 11)

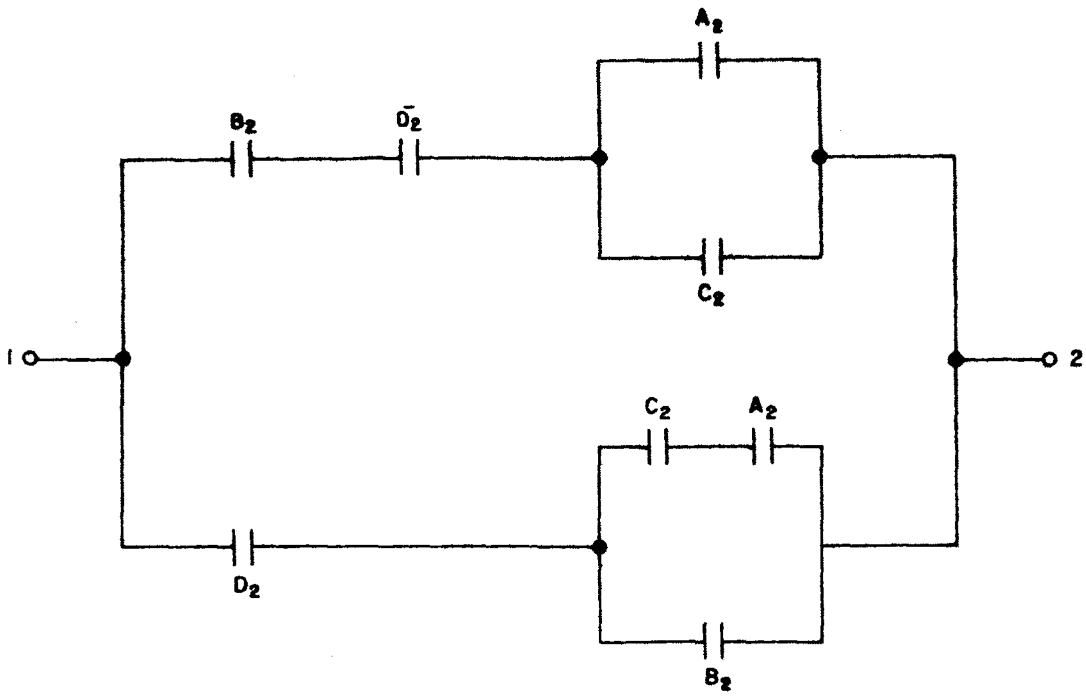
Designating W as the simplified Boolean expression yields:

$$W = A_2B_2\overline{D}_2 + B_2C_2\overline{D}_2 + \overline{B}_2D_2 + \overline{A}_2\overline{C}_2D_2$$

Factoring W results in a logical expression which requires fewer relay contacts in this implementation.

$$W = B_2\overline{D}_2(A_2 + C_2) + D_2(\overline{B}_2 + \overline{A}_2\overline{C}_2)$$

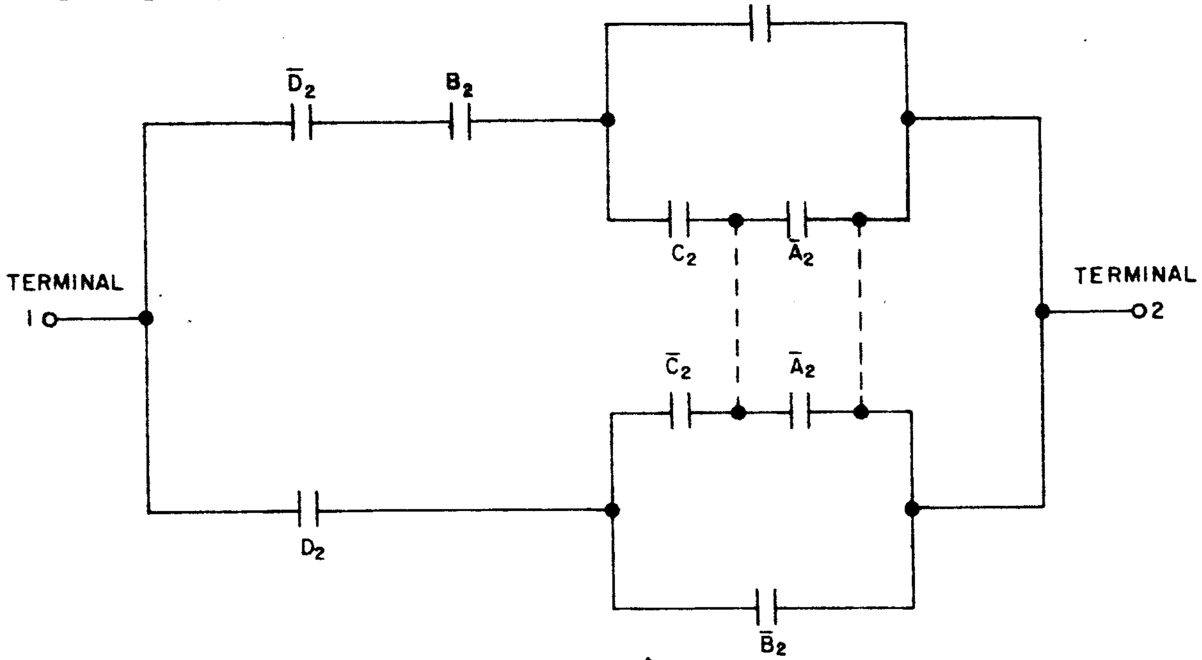
The following relay contact circuit satisfies this expression:



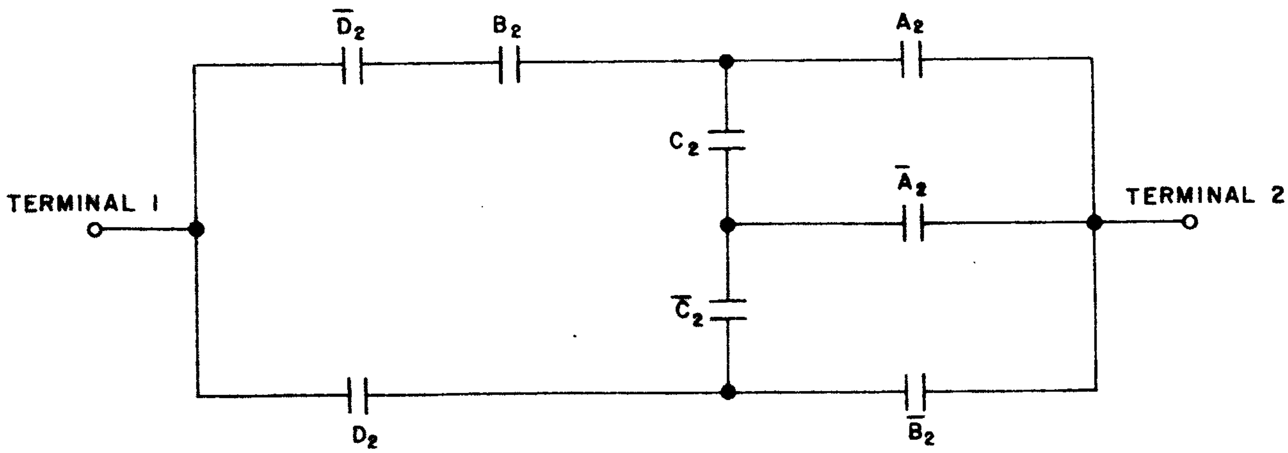
A short appears between terminals 1 and 2 only when the states of the A, B, C, D relays (associated with the second-least-significant digit) are such that they represent an odd decimal digit.

Further simplifications can be made by combining contacts (normally open and closed) of the same relay into transfer contacts, thus reducing the number of contact springs used in each case from 4 to 3. Interchanging the B and $\overline{D}$ contacts in the upper path permits the $\overline{D}$ and D contacts to combine into a transfer set. Also expanding $A_2 + C_2$ about A_2 by Shannon's expansion formula (Ref. 11) enables the formation of transfer contacts for A_2 and $\overline{A}_2$ and also C_2 and $\overline{C}_2$.

$A_2 + C_2 = A_2 + \bar{A}_2 C_2$



Combining the two $\bar{A}_2$ contacts into one set results in the final simplification.

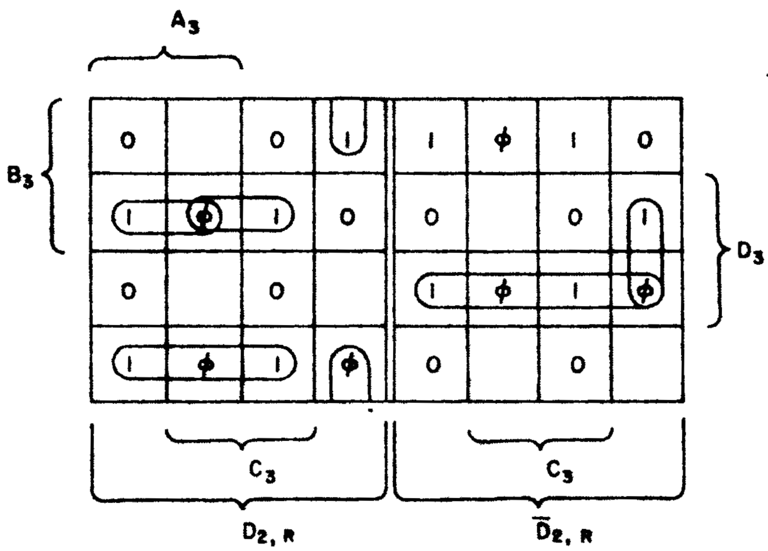


A voltage applied at terminal 1 appears at 2 in accordance with the table of combinations. The contacts of a relay coil placed between 2 and ground are used to reverse the A and C lines when energized. This circuit is shown in Fig. 25

The second-least-significant digit is 9's complemented when the third-least-significant digit (i.e., next-higher-order digit) is odd. In minimizing the logic to satisfy the 9's complementing requirement, a Veitch diagram for 5 variable entries is needed. The same procedure is adopted, starting with a table of combinations.

Third-Least-Significant Digit									
Decimal	Datex Code A_3	B_3	C_3	D_3	$D_{2,R}$	D_2	$D_{2,R}$	D_2
0	1	0	0	0	0	0	1	1
1	1	1	0	0	0	1	1	0
2	0	1	0	0	0	0	1	1
3	0	1	1	0	0	1	1	0
4	0	0	1	0	0	0	1	1
5	0	0	1	1	0	1	1	0
6	0	1	1	1	0	0	1	1
7	0	1	0	1	0	1	1	0
8	1	1	0	1	0	0	1	1
9	1	0	0	1	0	1	1	0

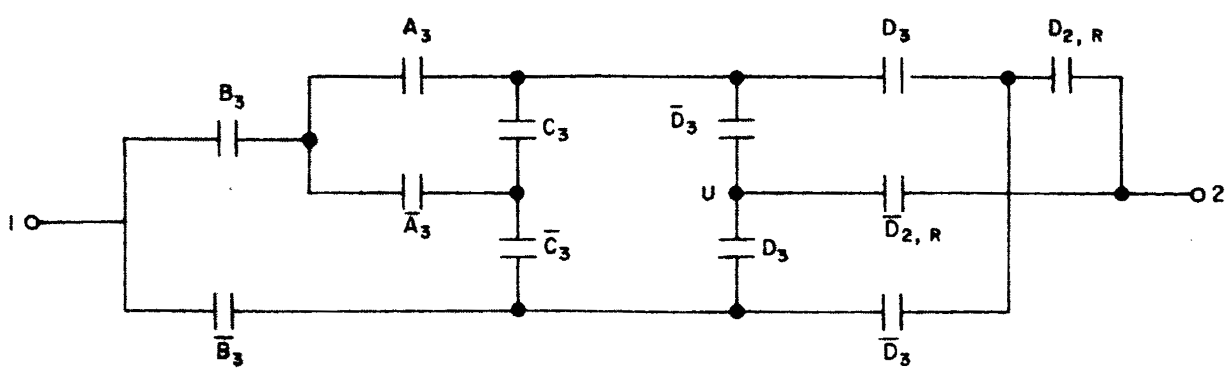
The D bit of the representation of the second-least-significant digit in reflected decimal is $D_{2,R}$. The D bit of the representation of the second-least-significant digit in true decimal (deg) is D_2. As shown in the above table of combinations, $D_{2,R}$ is inverted when the third-least-significant digit is odd. Inversion of a D bit results in the 9's complementation of the digit in question. Mapping the standard sum terms on a Veitch diagram follows:



A factored simplified logical expression of the 5 variable mapping is:

$$D_{2,R}\left[B_3D_3(A_3 + C_3) + D_3(B_3 + A_3C_3)\right] + \overline{D}_{2,R}\left[B_3\overline{D}_3(A_3 + C_3) + D_3(\overline{B}_3 + \overline{A}_3\overline{C}_3)\right]$$

By the judicious use of Shannon's expansion formula (standard sum form) and the combining of redundant contacts, further simplifications are made resulting in the use of a minimum number of relay contact springs. Following is a minimum relay logic circuit for the given table of combinations.



Terminal 1 will be connected to point U in the circuit when $D_{2,R}$ is to be inverted. If $D_{2,R}$ is a binary 0, $\overline{D}_{2,R}$ contacts are closed, and a short circuit appears between 1 and 2. Voltage applied to terminal 1 and ground will light the D_2 lamp connected from terminal 2 to ground. If $D_{2,R}$ is a binary 1, $\overline{D}_{2,R}$ contacts are open, resulting in an open circuit between 1 and 2. Therefore, the D_2 lamp will not be illuminated. In summarizing, odd third-least-significant digits give rise to $D_{2,R}$ inversions which becomes D_2 as tabulated:

$D_{2,R}$	D_2
0	1
1	0

Terminal 1 will be connected to point V when $D_{2,R}$ is not to be inverted. In this case, $D_{2,R}$ and D_2 will then be identical (i.e., an even third-least-significant digit dictates no 9's complementation).

Complete logic implementation for the second-least-significant digit is shown in Fig. 25 The derivation of 9's complementing logic for the second-highest-significant digit is left for the interested reader. (Note that since the highest significant digit never exceeds a decimal 3, a D_6 relay is not used.)

The lead-lag common selection of the coarse-count encoder disks is determined by the D bit of the highest significant digit of the next-higher-speed encoder disk (associated with the next-lower-order digit or digits). The leading (or lagging) disks' common brush is placed at a dc potential in accordance with the rules given in Section V-A2. Diodes placed in series with code sensing brushes of leading and lagging disks isolate the leading and lagging disks of a given set having the same common lead. If the coarse-count disks are properly phased or indexed with respect to a physically adjacent higher-speed disk, correct lead-lag selection takes place. The optimum offset of each coarse disk, as indicated in Section V-A2, is + 1/4 (leading) or - 1/4 (lagging) of its least count. To check or adjust the indexing of a coarse-count disk setting with respect to the adjacent higher-speed disk, the test unit may be used. As an example, assume that the first coarse-count disks are to be checked for indexing. The ± 1/4 of the first coarse-count disk's least count is equal to a 0.250 deg (+ 1/4 count) or a 0.750 deg (- 1/4 count) reading on the fine-count disk. Referring to Fig. 24, the following procedure is recommended.

1. Obtain a 750 setting for the three least-significant digits in true decimal. The reading of higher significant digits is immaterial.
2. Hold the coarse-count disk indexing switch in the up position.
3. By varying the setting in step 1 from 650 to 850, a transition should appear in one of the bits (i.e., lamps) associated with the first coarse-count disks. The 200-count variation is an allowable tolerance. The transition is a result of lead selection.
4. Step 3 is repeated for a 150 to 350 setting variation in true decimal of the three least-significant digits. A transition due to lag selection should appear in one of the bits associated with the first coarse-count disks. Should the transition not appear in the specified ranges, the housing of the first coarse-count disks must be rotated with respect to the housing of the fine count disk.

B. Binary Encoding Channel Test Unit

The operation and use of the binary test unit are the same as for the decimal test unit. Figure 26 is a photograph of the binary encoding channel test unit. The front panel controls are similar to the decimal test unit. Eighteen bits of binary are represented by on-off states of eighteen lamps grouped by threes for octal presentation (see Appendix A).

In the test mode, the binary test unit converts the reflected binary representation on the fine-count disk to a true binary indication. Relay logic shown in the schematic of the test unit, Fig. 27, is used to "exclusive or" the n binary bit with the n-1 reflected binary bit.

For checking the coarse-count disk indexing, the + 1/4 count offset is equivalent to a 512 fine count in binary and the - 1/4 count is equivalent to 2048 minus 512 or 1536 counts in binary. A ±200-count variation for the above is a practical tolerance in the lead-lag select transition region.

C. Encoding Disk Assembly Test Table

Since the antennas are not always available in the field, a means of using spare encoding disk assemblies for generating specific angles is convenient for test purposes. Test tables such as that shown in Fig. 27 were designed and machined at JPL for mounting spare encoding disk assemblies. Precision control of the angular setting of the disks is similar to that incorporated into the precision test fixtures. A lever arm utilizing a phosphor bronze flexure as a fulcrum is used to actuate a brake clamped to a circular wafer. The circular wafer in turn is rotated through angles which are a small fraction of the 0.18 and 0.175 deg of rotation required for a decimal and a binary count change, respectively.

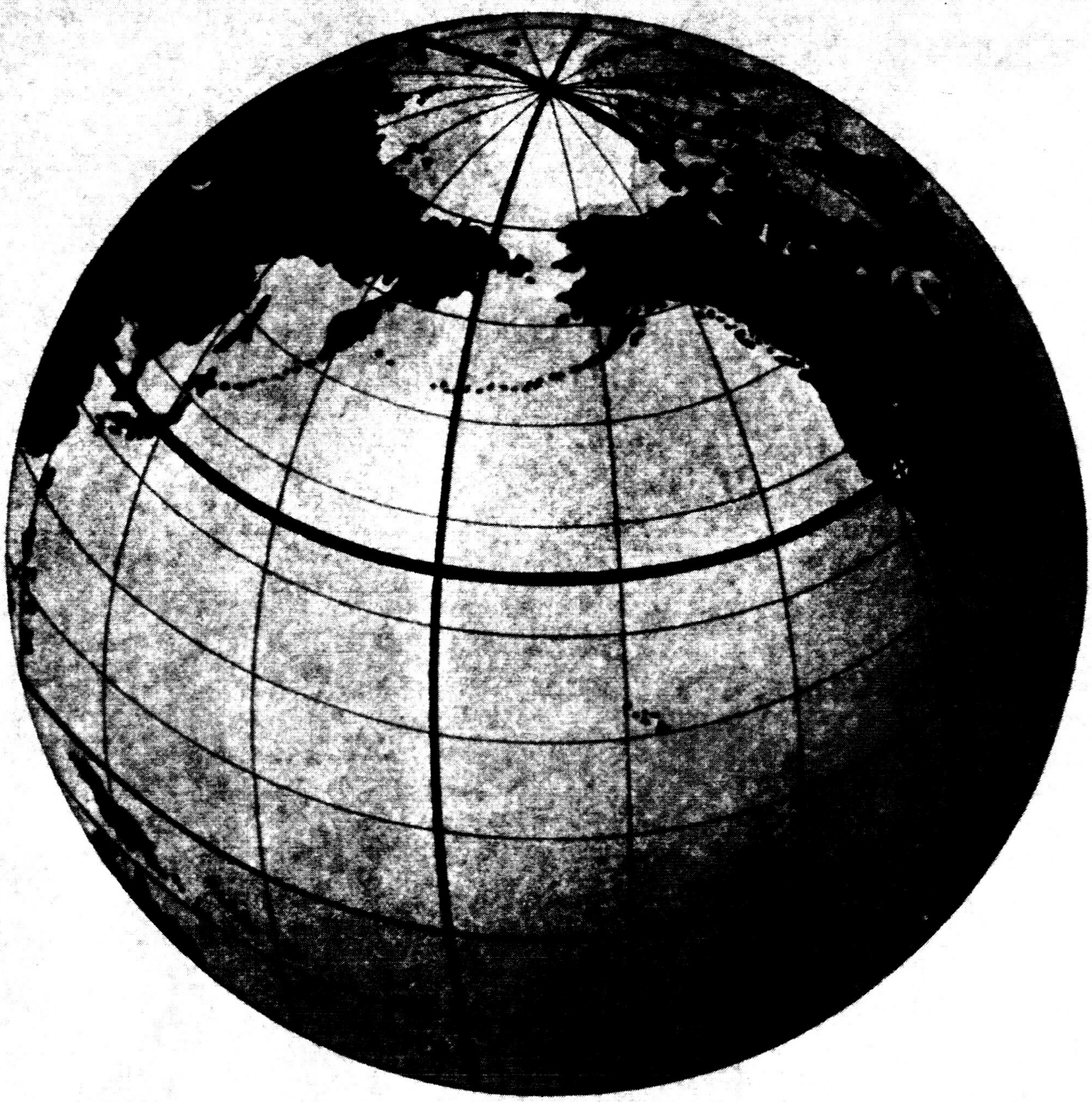


Table 1. Elevation decimal test results

Reading	X_{k_s} decimal degrees	X_k deg	X_k min	X_k sec	X_k decimal degrees	$X_{k_s} - X_k$	$X^* - (X_{k_s} - X_k)$
1	000.000	0	0	0	0.0	0	-0.002192
2	003.602	3	36	40.4	3.611222	-0.009222	0.007030
3	007.204	7	12	44.6	7.212388	-0.008388	0.006196
4	010.806	10	49	1.0	10.816944	-0.010944	0.008752
5	014.408	14	24	42.0	14.411666	-0.003666	0.001474
6	018.010	18	1	10.4	18.019555	-0.009555	0.007363
7	021.612	21	36	57.0	21.615833	-0.003833	0.001641
8	025.214	25	12	52.3	25.214527	-0.000527	-0.001665
9	028.816	28	49	21.2	28.822555	-0.006555	0.004363
10	032.418	32	25	3.3	32.417583	0.000417	-0.002609
11	036.020	36	1	40.4	36.027888	-0.007888	0.005696
12	039.622	39	37	1.0	39.616944	0.005056	-0.007248
13	043.224	43	13	53.8	43.231611	-0.007611	0.005419
14	046.826	46	49	55.5	46.832083	-0.006083	0.003891
15	050.428	50	26	32.4	50.442333	-0.014333	0.012141
16	054.030	54	1	33.4	54.025944	0.004056	-0.006248
17	057.632	57	37	57.7	57.632694	-0.000694	-0.001498
18	061.234	61	14	15.5	61.237638	-0.003648	0.001456
19	064.836	64	50	25.7	64.840472	-0.004472	0.002280
20	068.438	68	26	23.2	68.439777	-0.001777	-0.000415
21	072.040	72	2	29.5	72.041527	-0.001527	-0.000665
22	075.642	75	39	44.4	75.662333	-0.020333	0.018141
23	079.244	79	14	40.2	79.244500	-0.000500	-0.001692
24	082.846	82	47	7.6	82.785444	0.060556	-0.062748
25	086.448	86	27	12.8	86.453555	-0.005555	0.003363
26	090.050	90	3	10.0	90.052777	-0.002777	0.000585
27	093.652	93	38	41.6	93.644888	0.007112	-0.009304
28	097.254	97	15	43.3	97.262027	-0.008027	0.005835
29	100.856	100	47	33.3	100.792583	0.063417	-0.065609
30	104.458	104	27	33.0	104.459166	-0.001166	-0.001026
31	108.060	108	3	39.0	108.060833	-0.000833	-0.001359
32	111.662	111	39	40.8	111.661333	0.000667	-0.002859
33	115.264	115	16	3.1	115.267527	-0.003527	0.001335
34	118.866	118	51	50.3	118.863972	0.002028	-0.004220
35	122.468	122	28	42.5	122.478472	-0.010472	0.008280
36	126.070	126	4	32.0	126.075555	-0.005555	0.003363
37	129.672	129	40	7.1	129.668638	0.003362	-0.005554
38	133.274	133	16	23.7	133.273250	0.000750	-0.002942
39	136.876	136	52	41.9	136.878305	-0.002305	0.000113
40	140.478	140	29	9.2	140.485888	-0.007888	0.005696
41	144.080	144	4	54.6	144.081833	-0.001833	-0.000359
42	147.682	147	40	38.2	147.677277	0.004723	-0.006915
43	151.284	151	17	11.4	151.286500	-0.002500	0.000308
44	154.886	154	53	20.8	154.889111	-0.003111	0.000919
45	158.488	158	29	11.0	158.486388	0.001612	-0.003804
46	162.090	162	5	32.6	162.092388	-0.002388	0.000196
47	165.692	165	41	33.8	165.692722	-0.000722	-0.001470
48	169.294	169	17	46.0	169.296111	-0.002111	-0.000081
49	172.896	172	53	39.2	172.894222	0.001778	-0.003970
50	176.498	176	29	58.9	176.499694	-0.001694	-0.000498
51	180.100	180	6	7.6	180.102111	-0.002111	-0.000081
52	183.702	183	42	14.9	183.704138	-0.002138	-0.000054
53	187.304	187	18	23.7	187.306583	-0.002583	0.000391
54	190.906	190	54	45.6	190.904611	0.001389	-0.003581
55	194.508	194	31	15.4	194.520944	-0.012944	0.010752
56	198.110	198	7	53.5	198.131527	-0.021527	0.019335
57	201.712	201	43	17.3	201.721472	-0.009472	0.007280
58	205.314	205	18	59.0	205.316388	-0.002388	0.000196
59	208.916	208	55	24.4	208.923444	-0.007444	0.005252
60	212.518	212	31	13.8	212.520500	-0.002500	0.000308
61	216.120	216	07	35.9	216.126638	-0.006638	0.004446
62	219.722	219	43	36.3	219.726750	-0.004750	0.002558
63	223.324	223	19	48.8	223.330222	-0.006222	0.004030
64	226.926	226	55	51.3	226.930916	-0.004916	0.002724
65	230.528	230	32	8.0	230.535555	-0.007555	0.005363
66	234.130	234	8	10.9	234.136361	-0.006361	0.004169
67	237.732	237	44	5.2	237.734777	-0.002777	0.000585
68	241.334	241	20	10.3	241.336194	-0.002194	0.000002
69	244.936	244	56	44.7	244.945750	-0.009750	0.007558
70	248.538	248	32	26.6	248.540722	-0.002722	0.000530
71	252.140	252	8	23.7	252.139916	0.000084	-0.002276
72	255.742	255	44	56.0	255.748888	-0.006888	0.004696
73	259.344	259	20	2.1	259.333916	0.010084	-0.012276
74	262.946	262	57	14.0	262.953888	-0.007888	0.005696
75	266.548	266	33	8.2	266.552277	-0.004277	0.002085
76	270.150	270	9	20.3	270.155638	-0.005638	0.003446
77	273.752	273	45	7.9	273.752194	-0.000194	-0.001988
78	277.354	277	21	31.1	277.358638	-0.004638	0.002446
79	280.956	280	57	28.8	280.958000	-0.002000	-0.000192
80	284.558	284	34	10.6	284.569611	-0.011611	0.009419
81	288.160	288	9	57.1	288.165861	-0.005861	0.003669
82	291.762	291	45	51.2	291.764222	-0.002222	0.000030
83	295.364	295	22	22.1	295.372805	-0.008805	0.006613
84	298.966	298	57	58.5	298.966250	-0.000250	-0.001942
85	302.568	302	34	49.8	302.580500	-0.012500	0.010308
86	306.170	306	10	10.4	306.169555	0.000445	-0.002637
87	309.772	309	46	15.8	309.771055	0.000945	-0.003137
88	313.374	313	22	5.3	313.368138	0.005852	-0.008044
89	316.976	316	59	2.2	316.983944	-0.007944	0.005752
90	320.578	320	34	33.3	320.575916	0.002084	-0.004276
91	324.180	324	10	58.5	324.183194	-0.003194	0.001002
92	327.782	327	46	57.4	327.782611	-0.000611	-0.001581
93	331.384	331	23	17.3	331.388138	-0.004138	0.001946
94	334.986	334	59	1.0	334.983611	0.002389	-0.004581
95	338.588	338	35	47.0	338.596388	-0.008388	0.006196
96	342.190	342	11	38.4	342.194000	-0.004000	0.001808
97	345.792	345	47	7.7	345.785472	0.006528	-0.008720
98	349.394	349	23	30.7	349.391861	0.002139	-0.004331
99	352.996	352	59	53.3	352.998138	-0.002138	-0.000054
100	356.598	356	36	1.6	356.600444	-0.002444	0.000252
Closure	000.000	000	00	1.1	0.000305	0.000305	

Table 2. Elevation binary test results

Reading	Binary Count	Octal Count	decimal degrees (nearest lower)	deg	min	sec	X_k decimal degrees	X_{ks} decimal degrees	$X_{ks} - X_k$	$X^* - (X_{ks} - X_k)$
1	000 000	000 000	000 000	0	0	[illegible]	0 0	000 000000	0	0.002528
2	2 621	5 075	3 598	3	36	1[illegible].5	3 603472	3 599396	-0.004076	0.001548
3	5 242	12 172	7 198	7	12	[illegible].0	7 200833	7 198792	-0.002041	-0.000487
4	7 863	17 267	10 798	10	47	5[illegible].9	10 799416	10 798187	-0.001229	-0.001299
5	10 484	24 364	14 396	14	24	1[illegible].6	14 403222	14 397583	-0.005639	0.003111
6	13 105	31 461	17 996	18	00	[illegible].4	18 001777	17 996979	-0.004798	0.002270
7	15 726	36 556	21 596	21	36	2[illegible].0	21 607222	21 596375	-0.010847	0.008319
8	18 347	43 653	25 194	25	11	2[illegible].5	25 191527	25 195770	0.004243	0.006771
9	20 968	50 750	28 794	28	48	[illegible].0	28 800833	28 795166	-0.005667	0.003139
10	23 589	56 045	32 394	32	23	4[illegible].2	32 395333	32 394562	-0.000771	-0.001757
11	26 210	63 142	35 992	35	59	5[illegible].2	35 997833	35 993958	-0.003875	0.001347
12	28 831	70 237	39 592	39	35	5[illegible].9	39 599138	39 593353	-0.005785	0.003257
13	31 452	75 334	43 192	43	12	[illegible].8	43 220222	43 192749	-0.027473	0.024945
14	34 073	102 431	46 792	46	47	4[illegible].1	46 796416	46 792145	-0.004271	0.001743
15	36 694	107 526	50 390	50	23	2[illegible].0	50 390833	50 391541	0.000708	-0.003236
16	39 315	114 623	53 990	53	59	4[illegible].2	53 995055	53 990936	-0.004119	0.001591
17	41 936	121 720	57 590	57	35	2[illegible].9	57 589972	57 590332	0.000360	-0.002888
18	44 557	127 015	61 188	61	11	4[illegible].9	61 194972	61 189728	-0.005244	0.002716
19	47 178	134 112	64 788	64	47	2[illegible].3	64 791472	64 789124	-0.002348	-0.000180
20	49 799	141 207	68 388	68	23	2[illegible].3	68 390361	68 388519	-0.001842	-0.000686
21	52 420	146 304	71 986	71	59	[illegible].0	71 985833	71 987915	0.002082	-0.004610
22	55 041	153 401	75 586	75	35	2[illegible].9	75 591361	75 587730	-0.003631	0.001103
23	57 662	160 476	79 186	79	11	[illegible].5	79 183750	79 186707	0.002957	-0.005485
24	60 283	165 573	82 786	82	47	27.3	82 790916	82 786102	-0.004814	0.002286
25	62 904	172 670	86 384	86	23	2[illegible].9	86 389972	86 385498	-0.004474	0.001946
26	65 525	177 765	89 984	89	00	[illegible].8	89 001055	89 984938	-0.016117	0.013589
27	68 146	205 062	93 584	93	35	1[illegible].2	93 588388	93 584290	-0.004098	0.001570
28	70 767	212 157	97 182	97	11	2[illegible].0	97 188888	97 183685	-0.005203	0.002675
29	73 388	217 254	100 782	100	47	1[illegible].1	100 788638	100 783081	-0.005557	0.003029
30	76 009	224 351	104 382	104	22	2[illegible].1	104 374472	104 382477	0.008005	-0.010533
31	78 630	231 446	107 980	107	58	3[illegible].6	107 977111	107 981873	0.004762	-0.007290
32	81 251	236 543	111 580	111	34	2[illegible].2	111 573666	111 581268	0.007602	-0.010130
33	83 872	243 640	115 180	115	10	4[illegible].3	115 179527	115 180664	0.001137	-0.003665
34	86 493	250 735	118 780	118	46	2[illegible].6	118 774333	118 780060	0.005727	-0.008255
35	89 114	256 032	122 378	122	22	1[illegible].0	122 370555	122 379456	0.008901	-0.011429
36	91 735	263 127	125 978	125	59	[illegible].7	125 984083	125 978851	-0.005232	0.002704
37	94 356	270 224	129 578	129	34	2[illegible].9	129 574972	129 578247	0.003275	-0.005803
38	96 977	275 321	133 176	133	10	3[illegible].2	133 175333	133 177643	0.002310	-0.004838
39	99 598	302 416	136 776	136	46	4[illegible].6	136 779888	136 777039	-0.002849	0.000321
40	102 219	307 513	140 376	140	22	2[illegible].2	140 373944	140 376434	0.002490	-0.005018
41	104 840	314 610	143 974	143	58	4[illegible].0	143 979444	143 975830	-0.003614	0.001086
42	107 461	321 705	147 574	147	34	34.1	147 576138	147 575226	-0.000912	-0.001616
43	110 082	327 002	151 174	151	10	2[illegible].4	151 174833	151 174622	-0.000211	-0.002317
44	112 703	334 077	154 774	154	46	2[illegible].7	154 773527	154 774017	0.000490	-0.003018
45	115 324	341 174	158 372	158	22	20.0	158 372222	158 373130	0.000915	-0.003443
46	117 945	346 271	161 972	161	58	3[illegible].8	161 975500	161 972809	-0.002691	0.000163
47	120 566	353 366	165 572	165	34	1[illegible].9	165 570805	165 572205	0.001400	-0.003928
48	123 187	360 463	169 170	169	10	2[illegible].1	169 174750	169 171600	-0.003150	0.000622
49	125 808	365 560	172 770	172	46	1[illegible].4	172 770111	172 770996	0.000885	-0.003413
50	128 429	372 655	176 370	176	22	3[illegible].8	176 375777	176 370392	-0.005385	0.002857
51	131 050	377 752	179 968	179	58	1[illegible].4	179 970388	179 969788	-0.000600	-0.001928

Reading	Binary Count	Octal Count	decimal degrees (nearest lower)	deg	min	sec	X_k decimal degrees	X_{ks} decimal degrees	$X_{ks} - X_k$	$X^* - (X_{ks} - X_k)$
52	133 671	405 047	183 568	183	34	13.3	183 570361	183 569183	-0.001178	-0.001350
53	136 292	412 144	187 168	187	9	52.8	187 164666	187 168579	0.003913	-0.006441
54	138 913	417 241	190 766	190	46	2.7	190 767416	190 767975	0.000559	-0.003087
55	141 534	424 336	194 366	194	22	22.2	194 372833	194 367371	-0.005462	0.002934
56	144 155	431 433	197 966	197	57	53.7	197 964916	197 966766	-0.001850	-0.004378
57	146 776	436 530	201 566	201	34	9.5	201 569305	201 566162	-0.003143	0.000615
58	149 397	443 625	205 164	205	9	45.6	205 162666	205 165558	0.002892	-0.005420
59	152 018	450 722	208 764	208	46	16.9	208 771361	208 764954	-0.006407	0.003879
60	154 639	456 017	212 364	212	21	58.2	212 366166	212 364349	-0.001817	-0.000711
61	157 260	463 114	215 962	215	58	18.0	215 971666	215 963745	-0.007921	0.005393
62	159 881	470 211	219 562	219	33	55.2	219 565333	219 563141	-0.002192	-0.000336
63	162 502	475 306	223 162	223	9	40.6	223 161277	223 162537	0.001260	-0.003788
64	165 123	502 403	226 760	226	45	56.0	226 765555	226 761932	-0.003623	0.001095
65	167 744	507 500	230 360	230	22	1.6	230 367111	230 360328	-0.006783	0.004255
66	170 365	514 575	233 960	233	57	41.8	233 961611	233 960724	-0.000887	-0.001641
67	172 986	521 672	237 560	237	33	42.4	237 561777	237 560120	-0.001657	-0.000871
68	175 607	526 767	241 158	241	9	55.9	241 165527	241 159515	-0.006012	0.003484
69	178 228	534 064	244 758	244	45	57.1	244 765861	244 758911	-0.006950	0.004422
70	180 849	541 161	248 358	248	21	58.5	248 366250	248 358807	-0.007443	0.004915
71	183 470	546 256	251 956	251	57	40.5	251 961250	251 957703	-0.003547	0.001019
72	186 091	553 353	255 556	255	33	50.4	255 564000	255 557098	-0.006902	0.004374
73	188 712	560 450	259 156	259	9	24.0	259 156666	259 156494	-0.000172	-0.002356
74	191 333	565 545	262 754	262	45	55.0	262 765277	262 755890	-0.009387	0.006859
75	193 954	572 642	266 354	266	21	29.4	266 358166	266 355286	-0.002880	0.000352
76	196 575	577 737	269 954	269	57	36.1	269 959750	269 954681	-0.005069	0.002541
77	199 196	605 034	273 554	273	33	17.6	273 554888	273 554077	-0.000811	-0.001717
78	201 817	612 131	277 152	277	9	25.3	277 157027	277 153473	-0.003554	0.001026
79	204 438	617 226	280 752	280	45	24.6	280 756833	280 752869	-0.003964	0.001436
80	207 059	624 323	284 352	284	21	13.7	284 353805	284 352264	-0.001541	-0.000987
81	209 680	631 420	287 950	287	57	22.6	287 956277	287 951660	-0.004617	0.002089
82	212 301	636 515	291 550	291	33	18.8	291 555222	291 551056	-0.004166	0.001638
83	214 922	643 612	295 150	295	9	20.1	295 155583	295 150452	-0.005131	0.002603
84	217 543	650 707	298 748	298	44	49.5	298 747083	298 749847	-0.002764	-0.005292
85	220 164	656 004	302 348	302	21	35.0	302 359722	302 349243	-0.010479	0.007951
86	222 785	663 101	305 948	305	57	4.4	305 951222	305 948639	-0.002583	0.000055
87	225 486	670 176	309 656	309	33	18.8	309 555222	309 548035	-0.007187	0.004659
88	228 027	675 273	313 146	313	8	51.1	313 147527	313 147430	-0.000097	-0.002431
89	230 648	702 370	316 746	316	45	11.0	316 753055	316 746826	-0.006229	0.003701
90	233 269	707 465	320 346	320	20	46.6	320 346277	320 346222	-0.000055	-0.002473
91	235 890	714 562	323 444	323	56	55.6	323 948777	323 945618	-0.003159	0.000631
92	238 511	721 657	327 544	327	32	12.4	327 536777	327 545013	0.008236	-0.010764
93	241 132	726 754	331 144	331	8	42.0	331 145000	331 144409	-0.000591	-0.001937
94	243 753	734 051	334 742	334	44	37.1	334 743638	334 743805	0.000167	-0.002695
95	246 374	741 146	338 342	338	21	7.6	338 352111	338 343201	-0.008910	0.006382
96	248 995	746 243	341 942	341	57	2.2	341 950611	341 942596	-0.008015	0.005487
97	251 616	753 340	345 542	345	32	25.6	345 540444	345 542992	0.002548	-0.005076
98	254 637	760 435	349 690	349	8	42.8	349 145222	349 142388	-0.002834	0.000306
99	256 858	765 532	352 740	352	44	51.3	352 747583	352 740784	-0.006799	0.004271
100	259 479	772 627	356 340	356	20	31.4	356 342055	356 340179	-0.001876	-0.000652
101	262 100	777 724	359 938	359	56	18.5	359 938472	359 939575	0.001103	-0.003631
Closure	000 000			359	59	59.2	359 999777	000 000000	-0.000223	

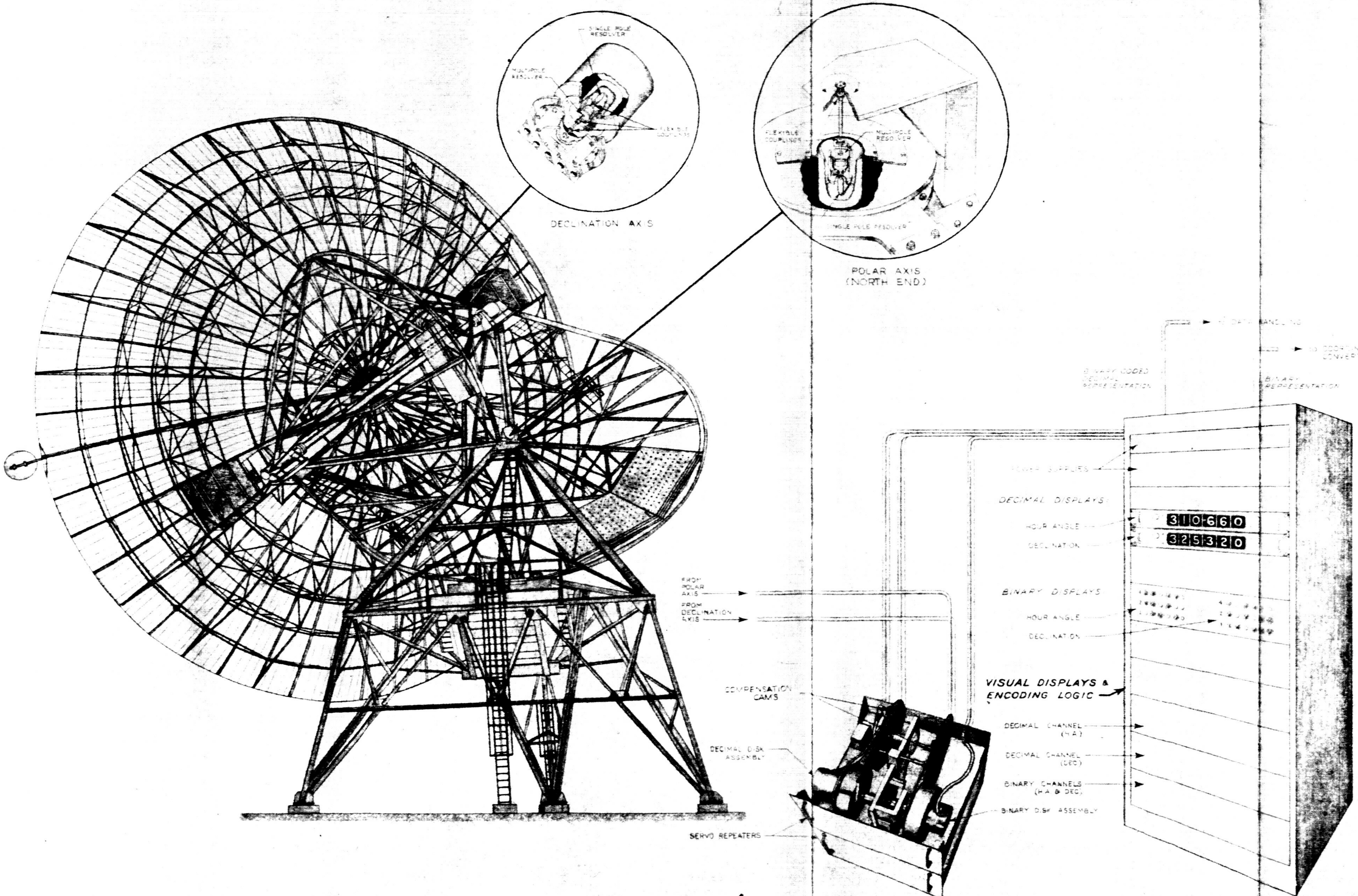


Fig. 1. Angular encoding systems, receiving antenna

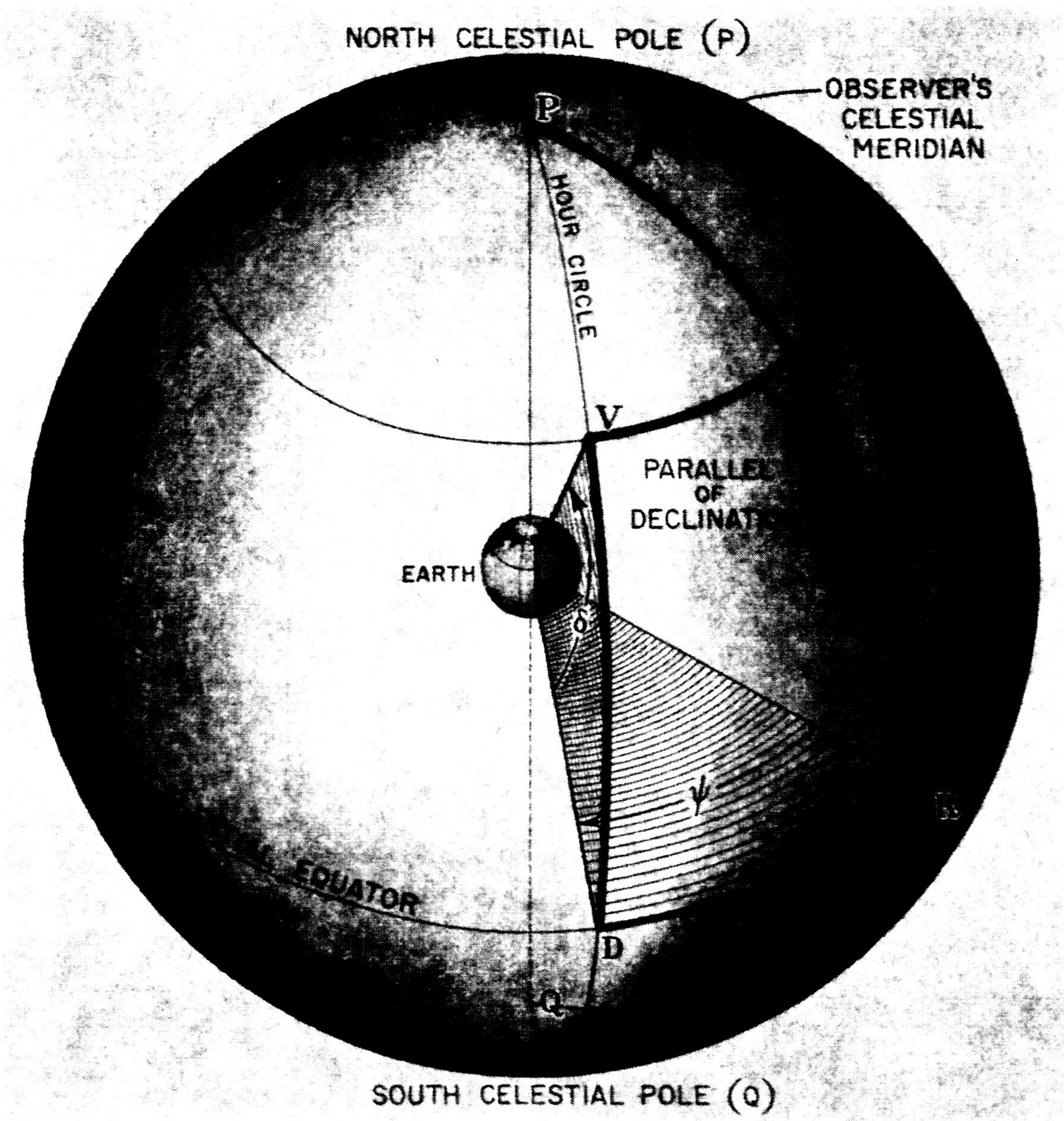


Fig. 2. Local hour angle and declination of a spacial point

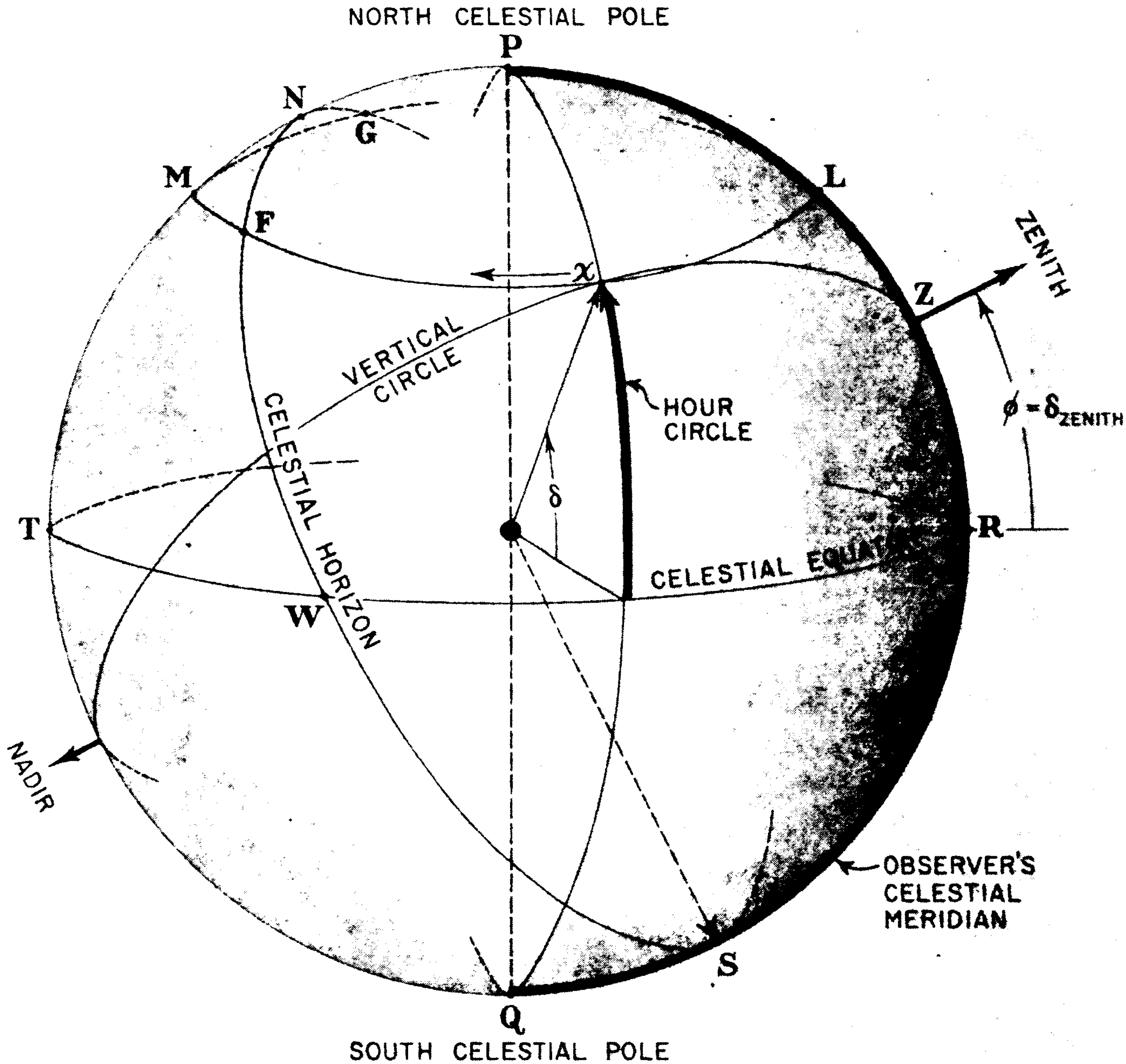


Fig. 3. Observed position of a star in the equatorial system

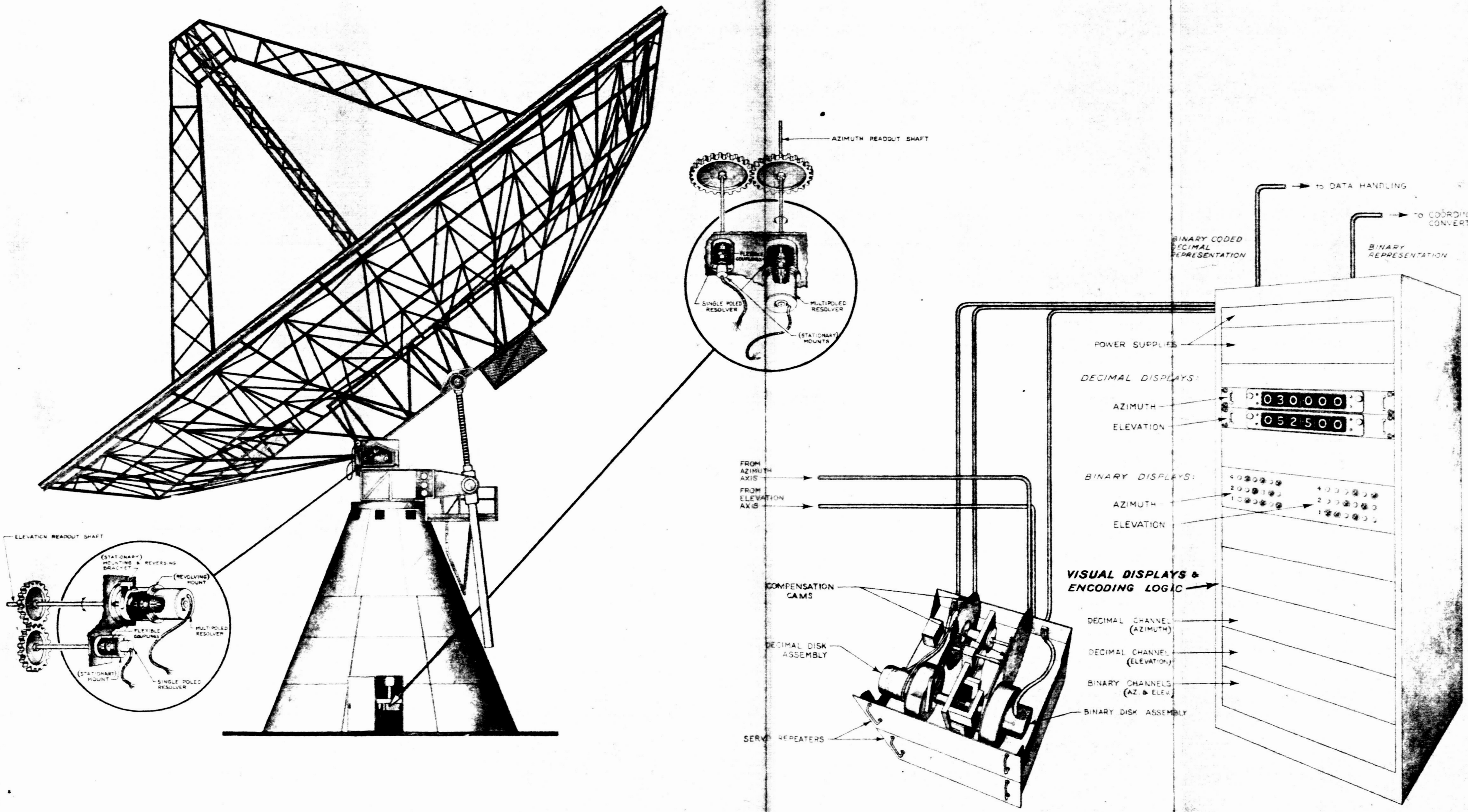


Fig. 4. Angular encoding systems, transmitting antenna

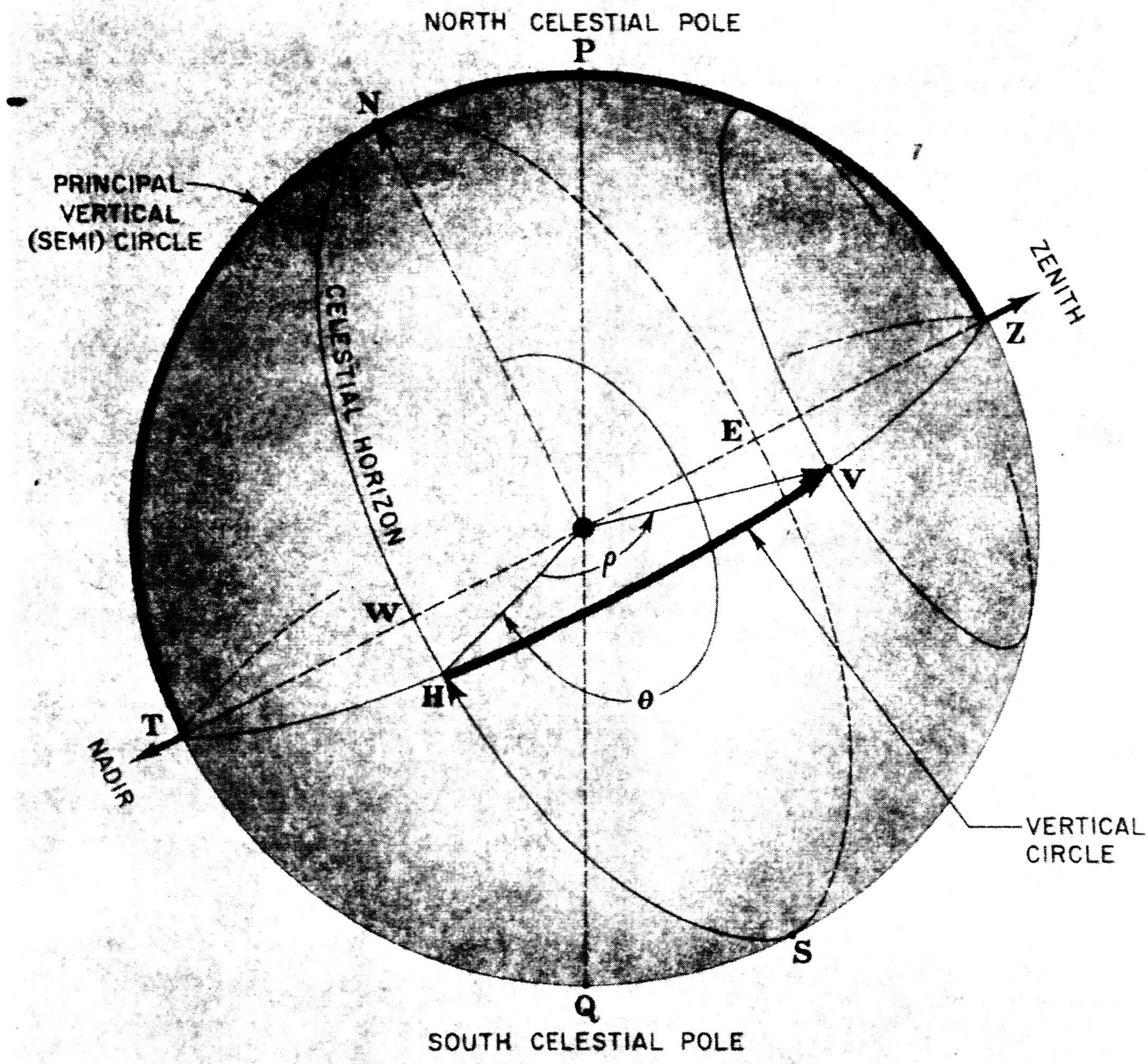


Fig. 5. Aximuth and elevation of a spacial point

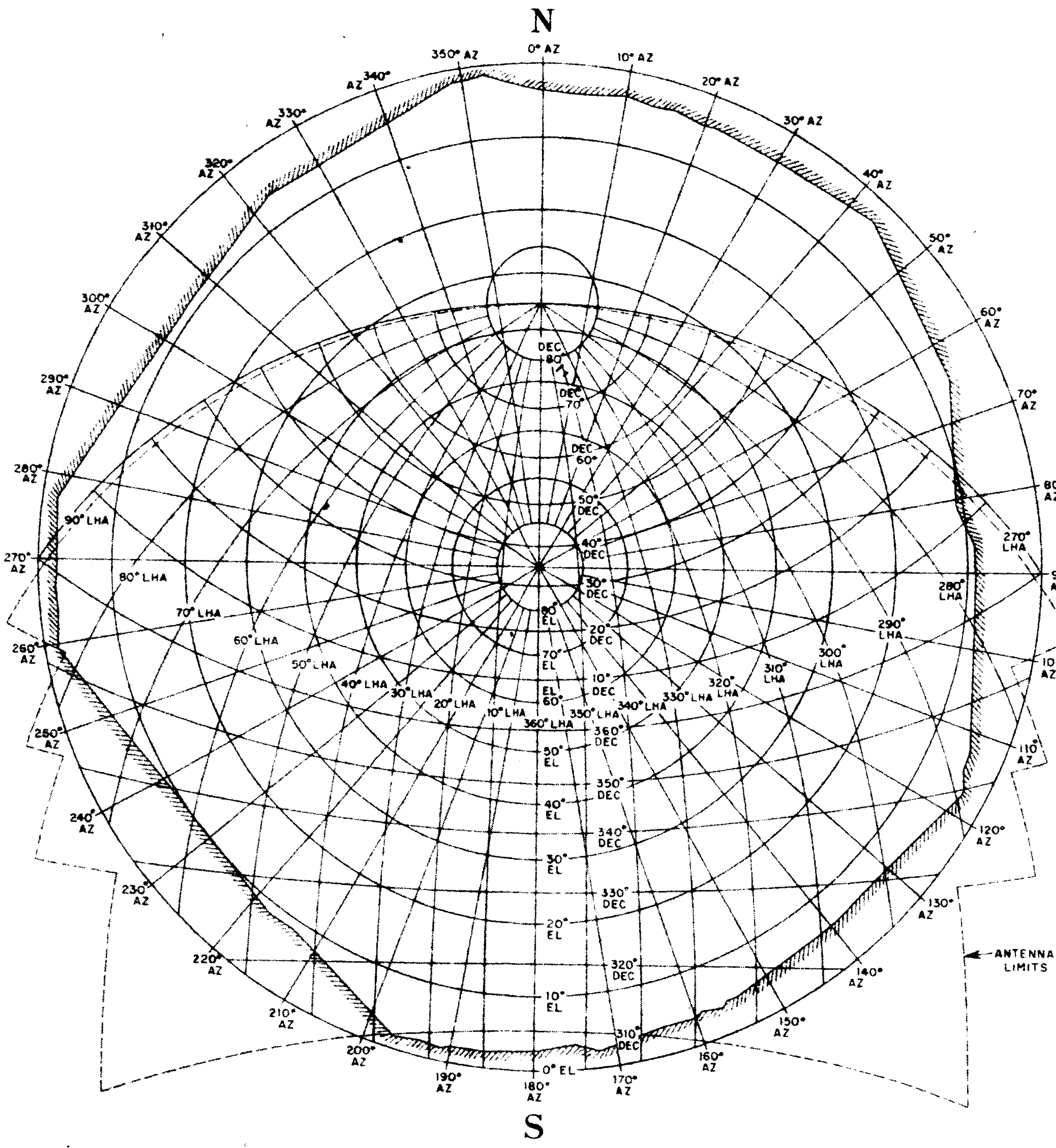


Fig. 6. Contours of constant LHA, δ, and Az-El Goldstone antenna angles

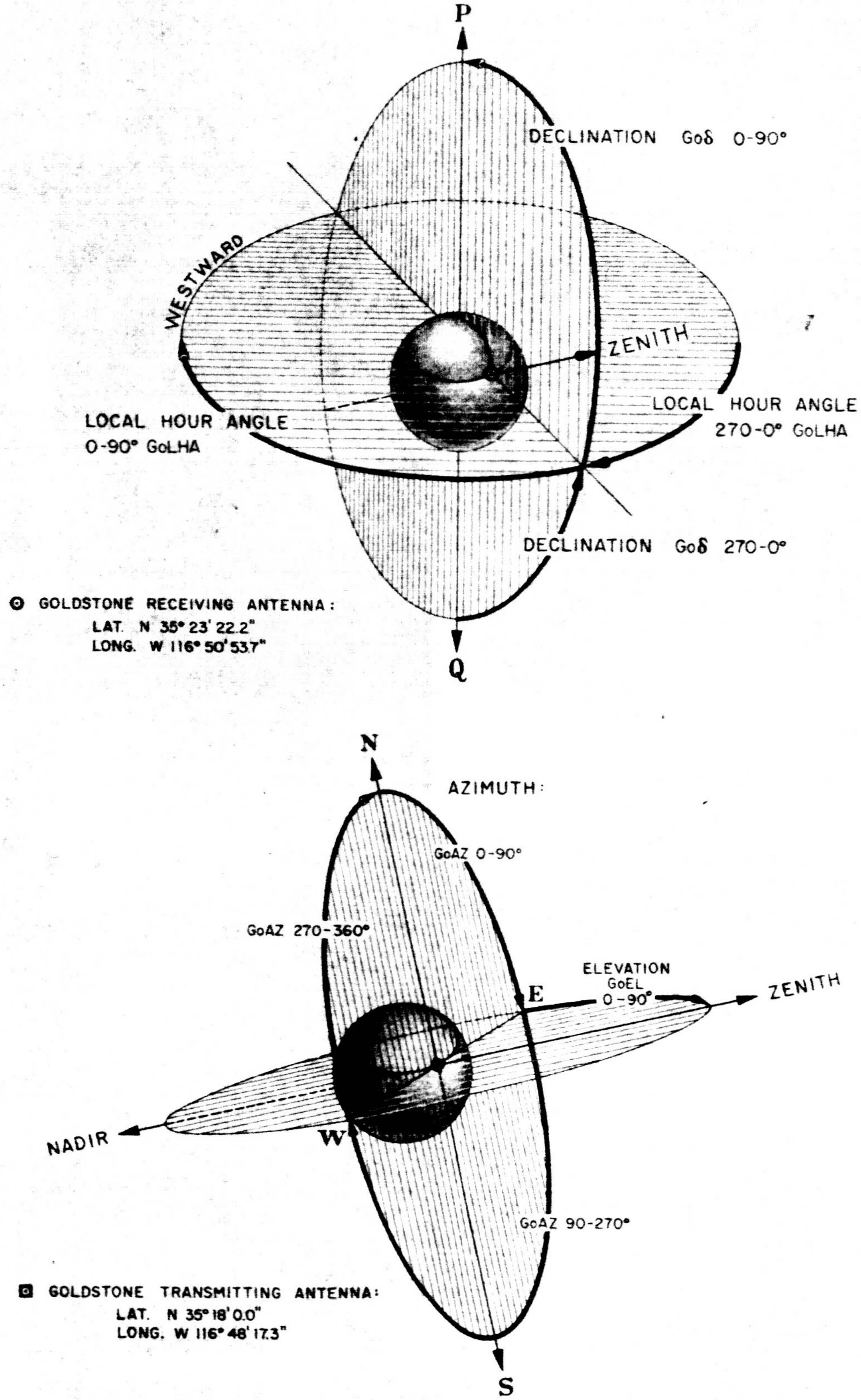


Fig. 7. Measurements of local hour angle, declination, azimuth, and elevation

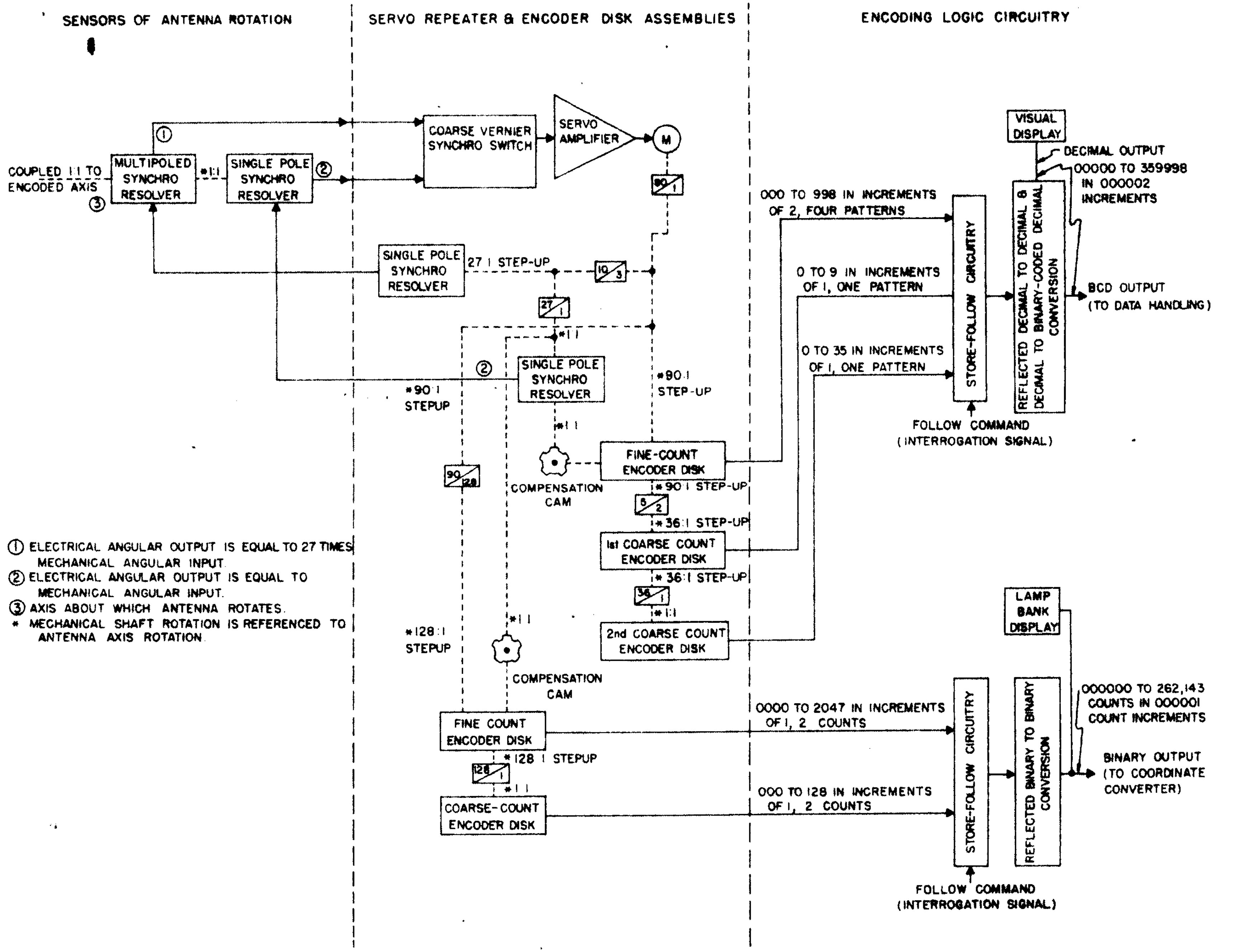


Fig. 8. Encoding system for each axis of the Goldstone antennas

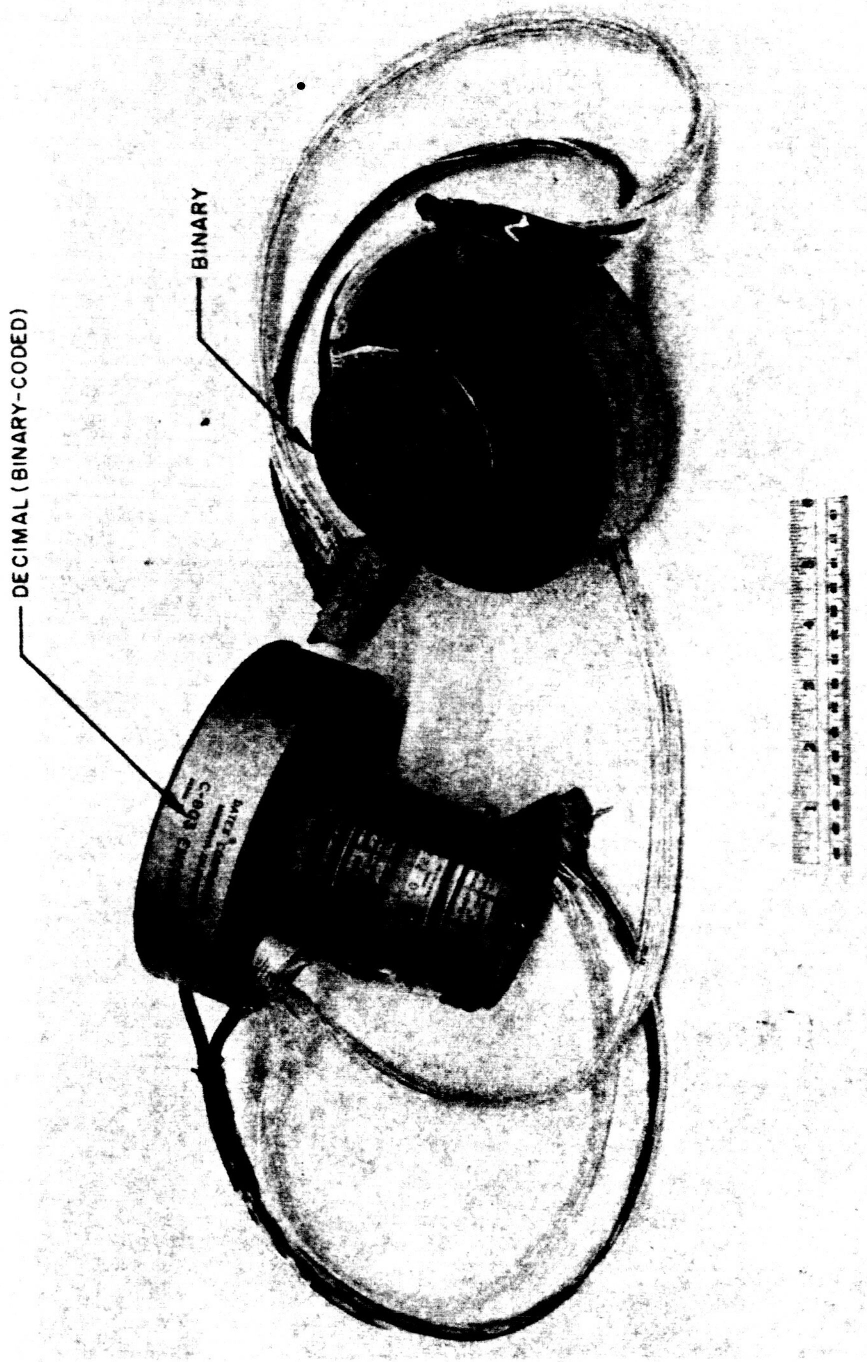


Fig. 9. Encoding disk assemblies

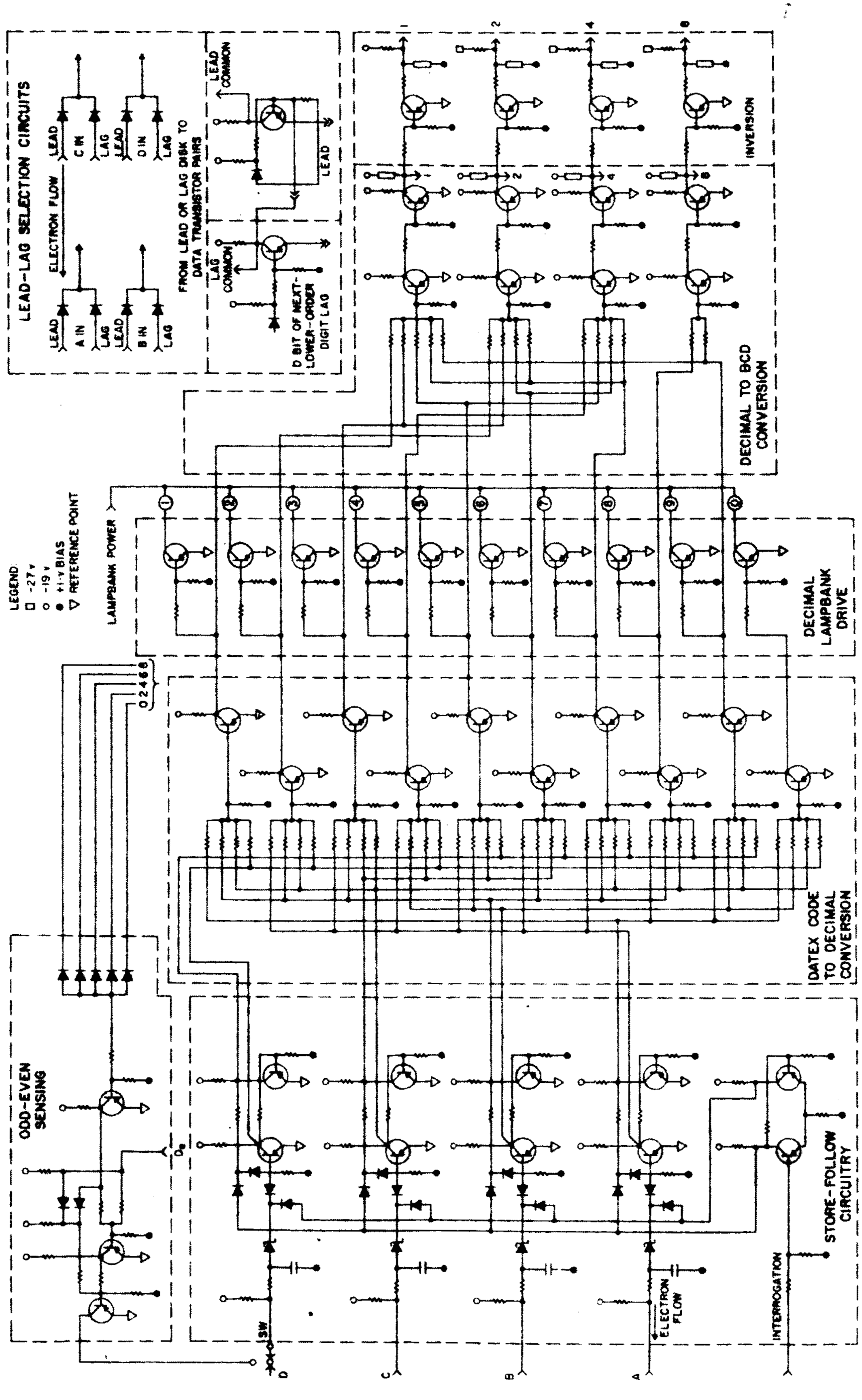


Fig. 10. Decimal encoding logic

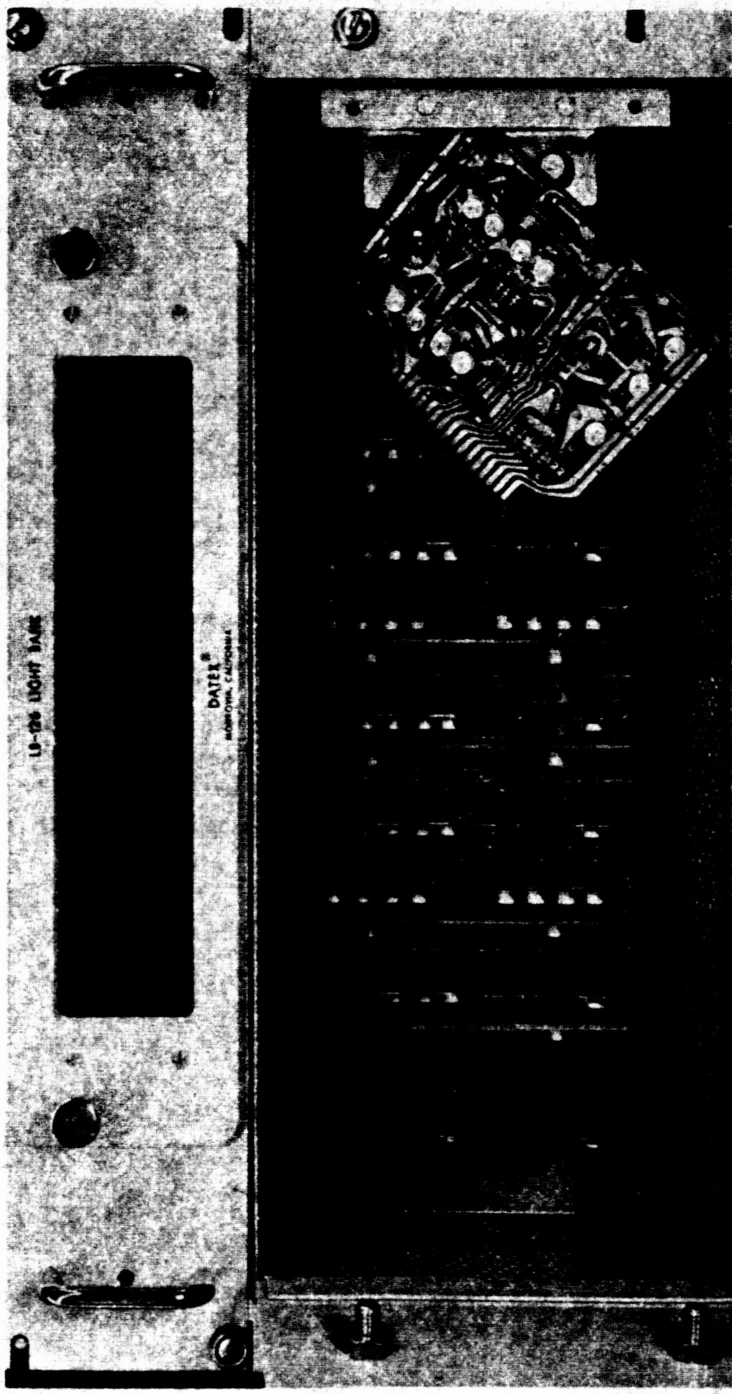


Fig. 11. Decimal encoding logic and light bank

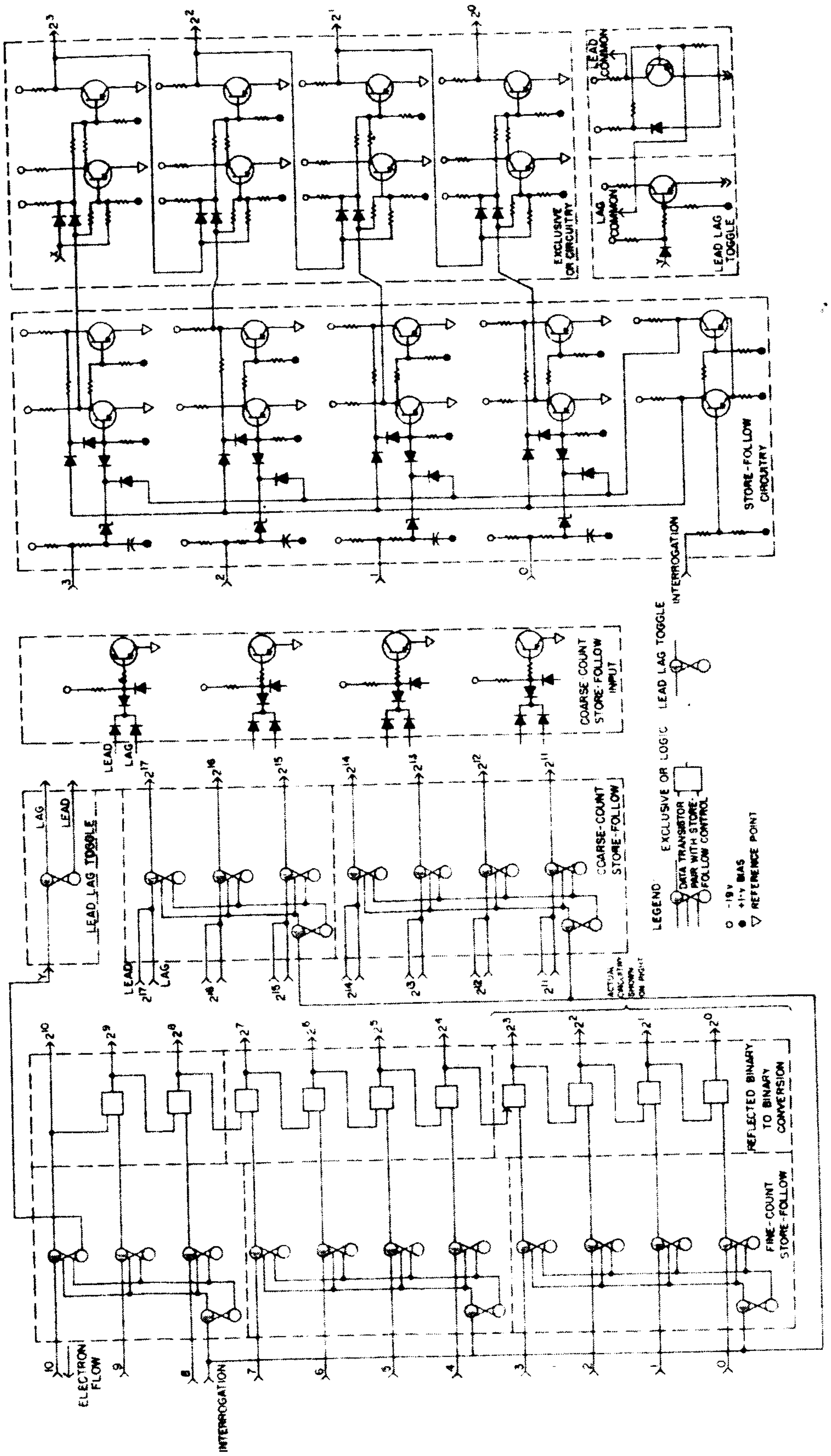


Fig. 12. Binary encoding logic

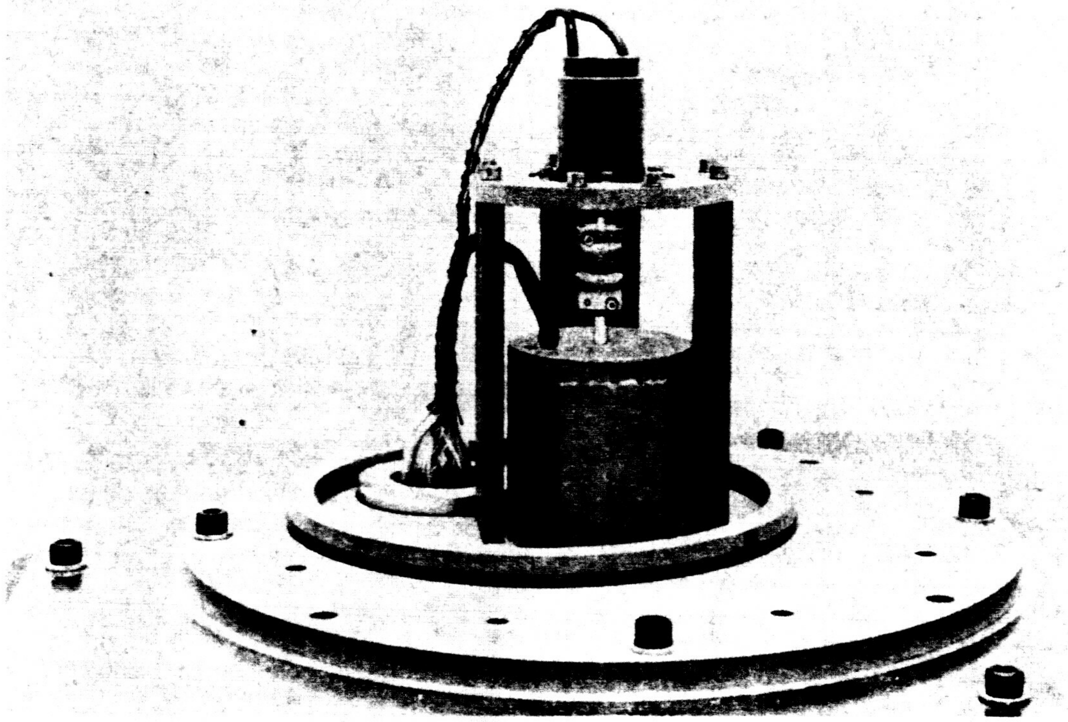


Fig. 13. Multipoled and single-poled resolvers

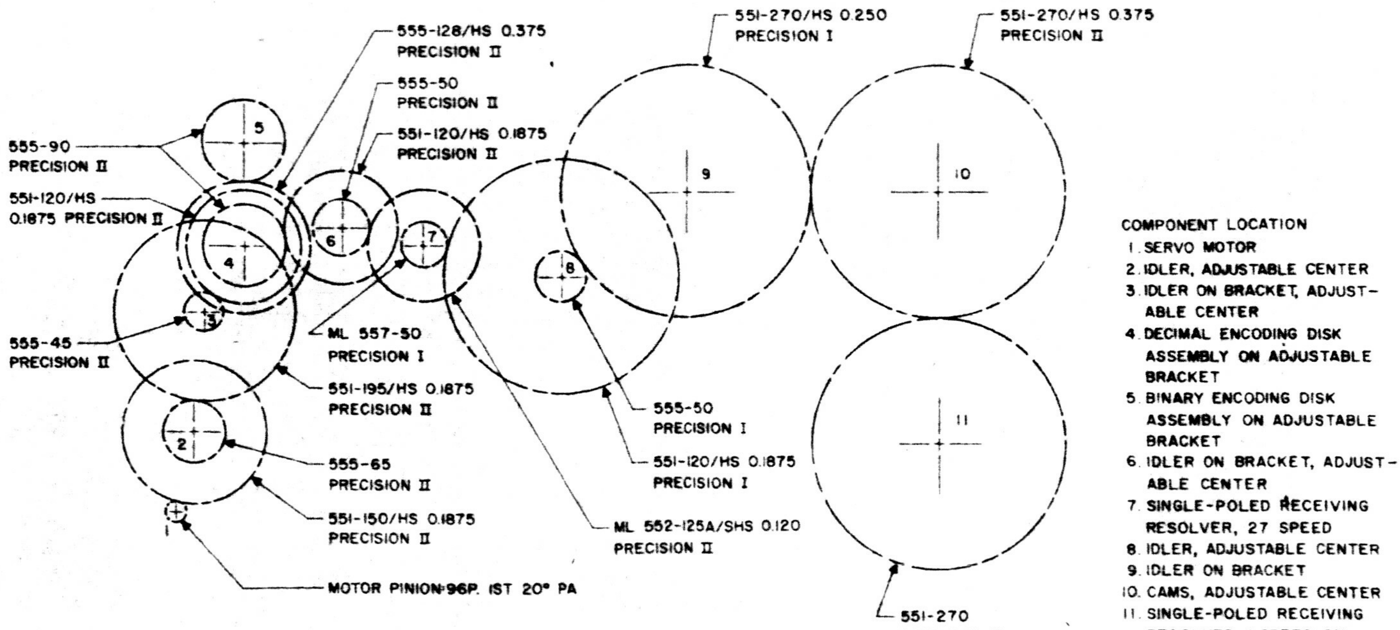


Fig. 14. Servo repeater gearing

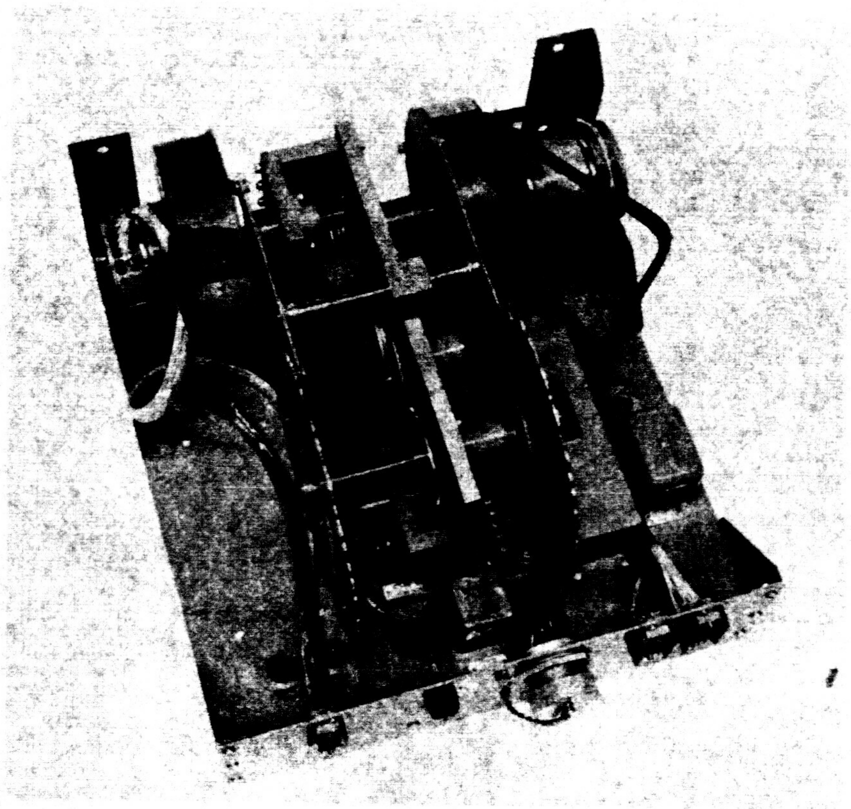


Fig. 15. Servo repeater and disk assemblies

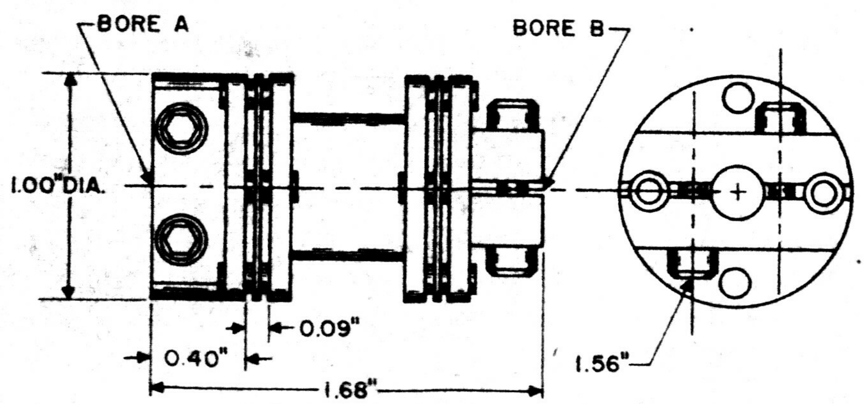


Fig. 16. Coupling assembly

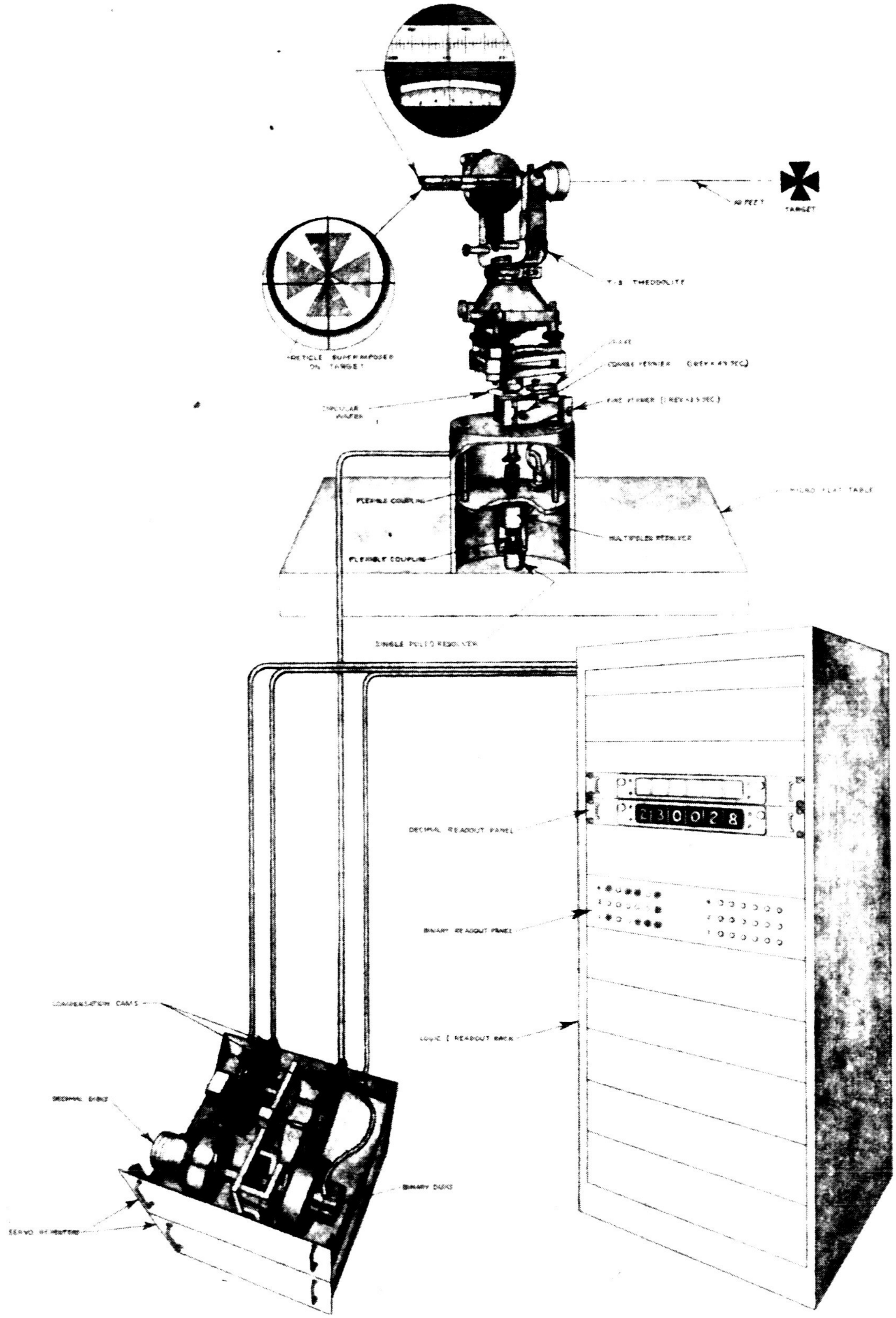


Fig. 17. Accuracy test setup

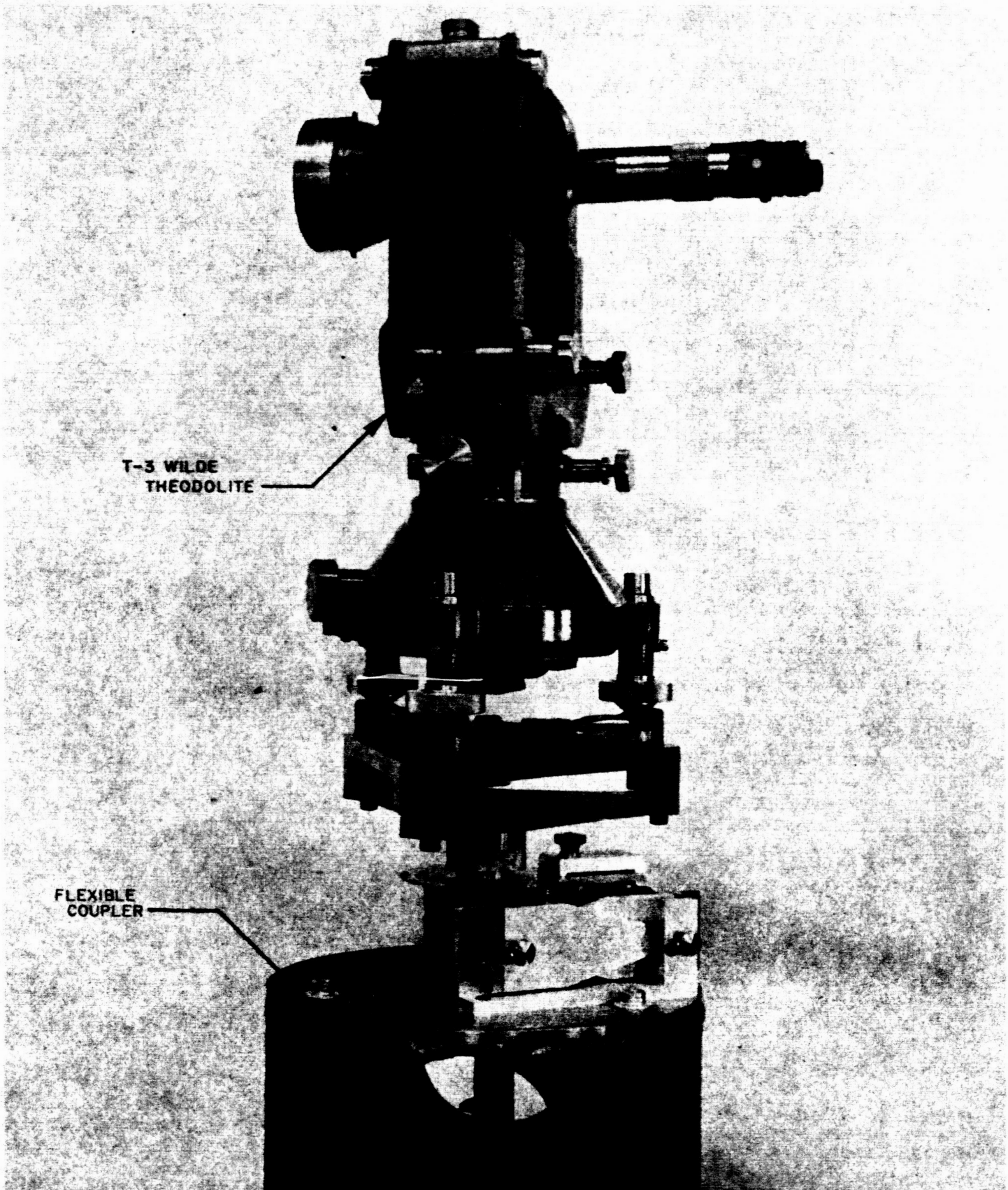


Fig. 18. Precision test fixture

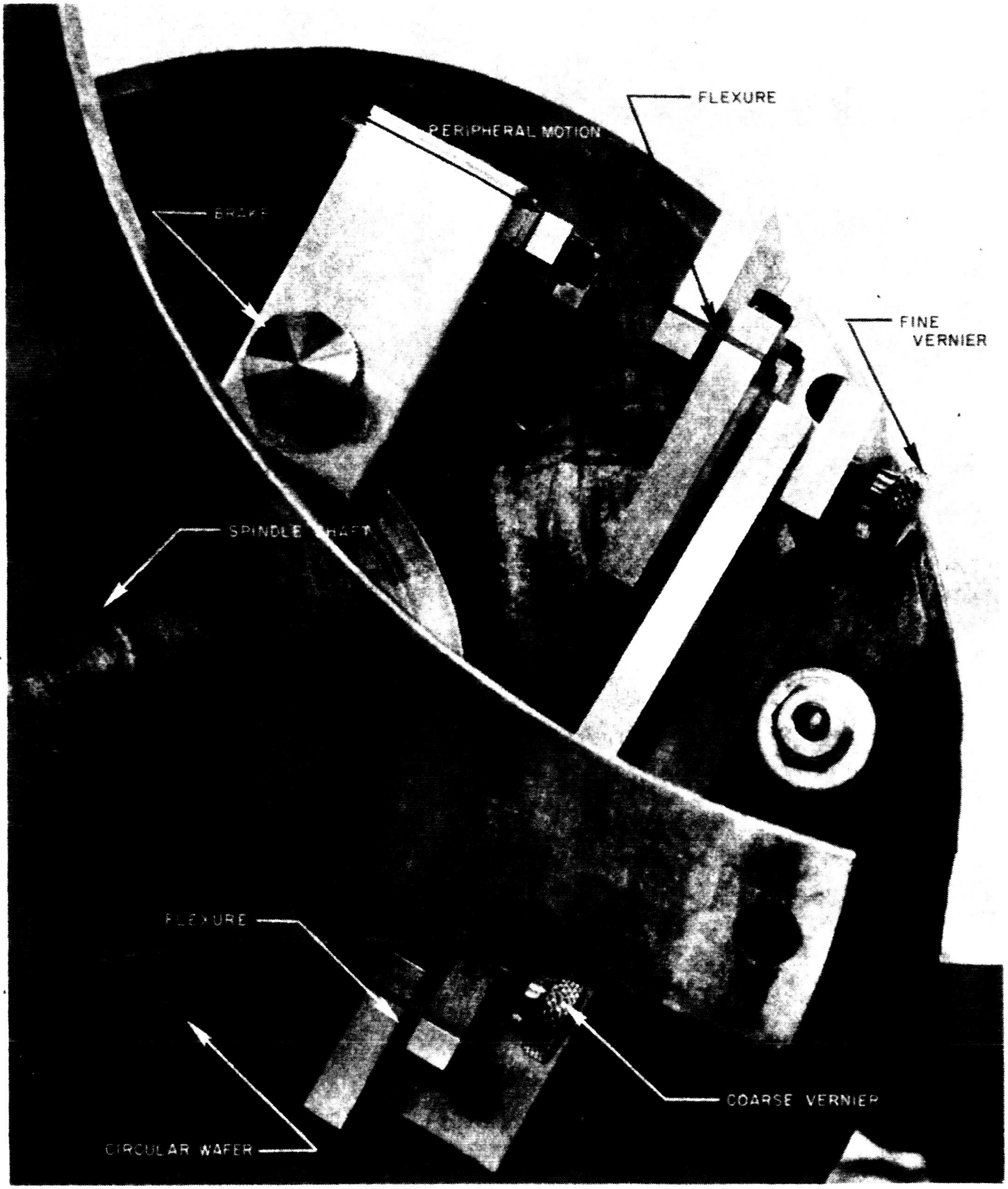


Fig. 19. Brake assembly and vernier controls

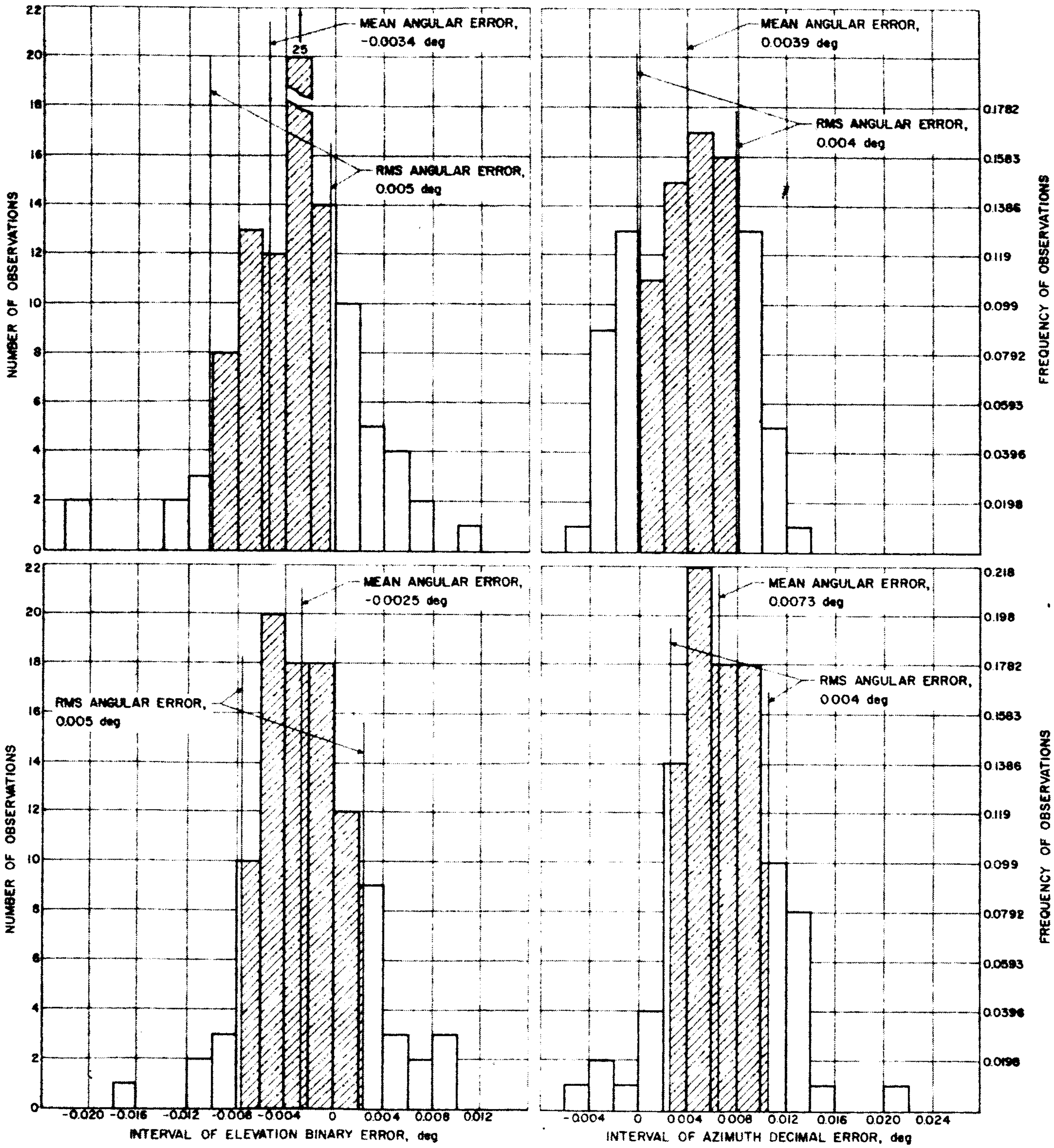


Fig. 20. Distribution of encoding errors for azimuth and elevation axes

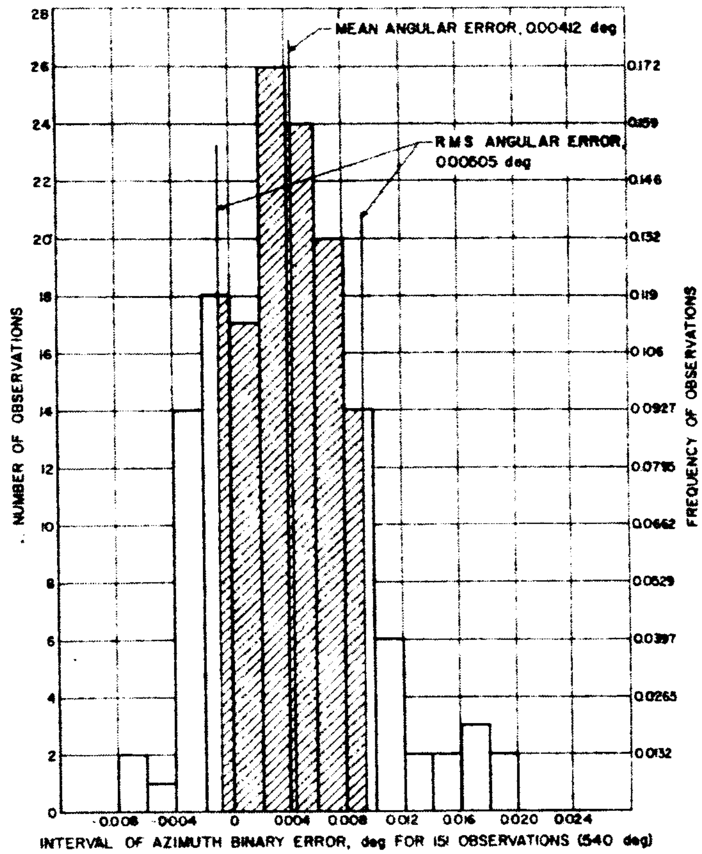


Fig. 21. Error distribution of azimuth binary channel (for 540 deg)

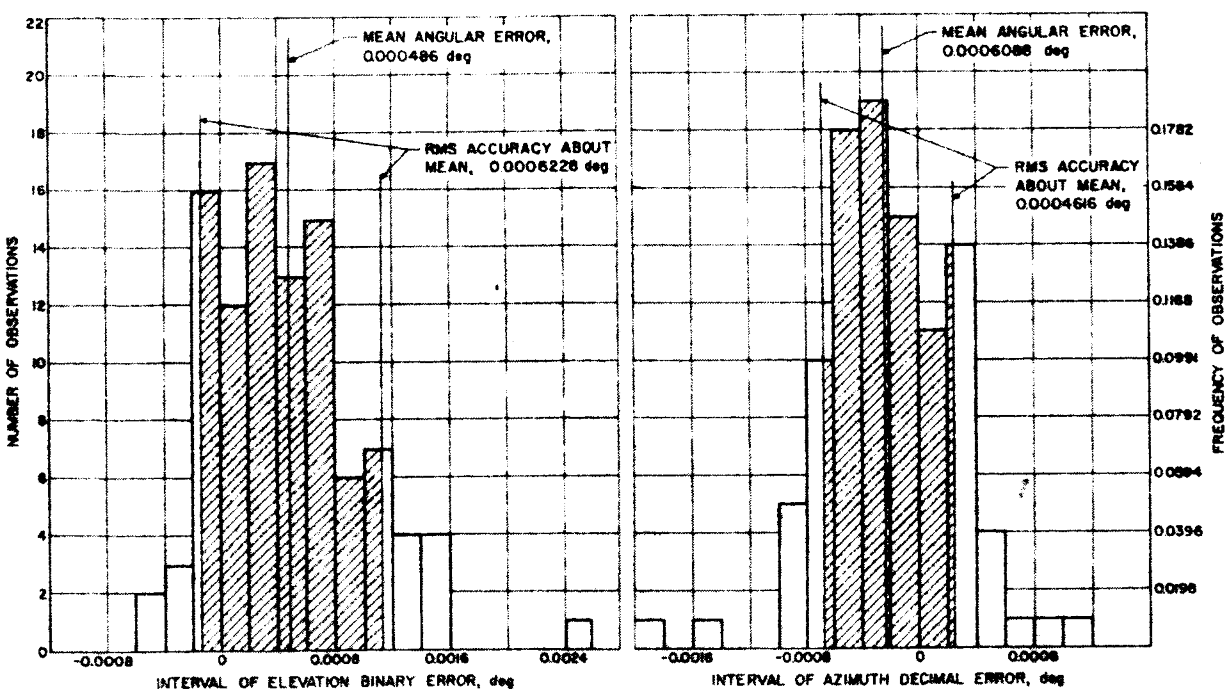


Fig. 22. Distribution of encoding disk assembly errors

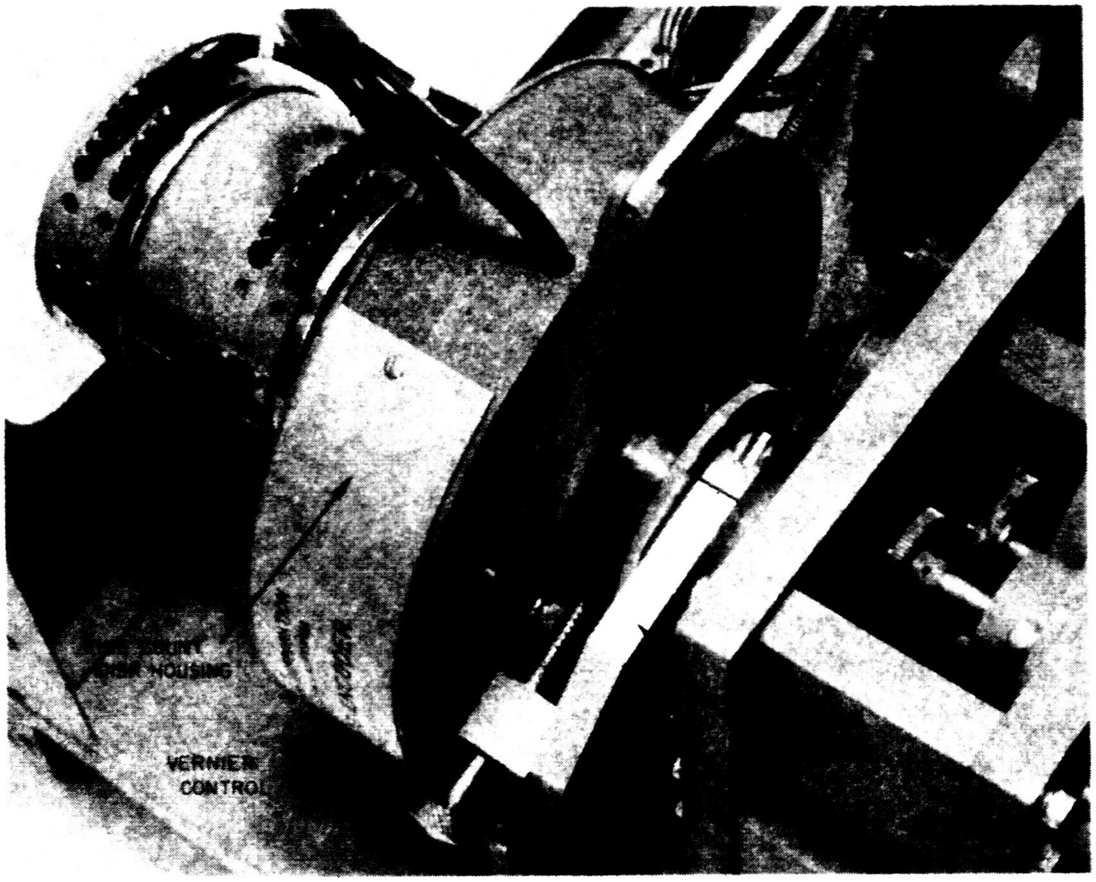


Fig. 23. Indexing fixture

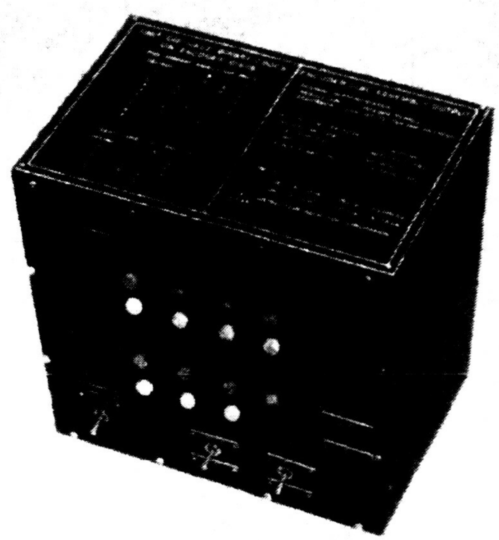


Fig. 24. Decimal encoding channel test unit

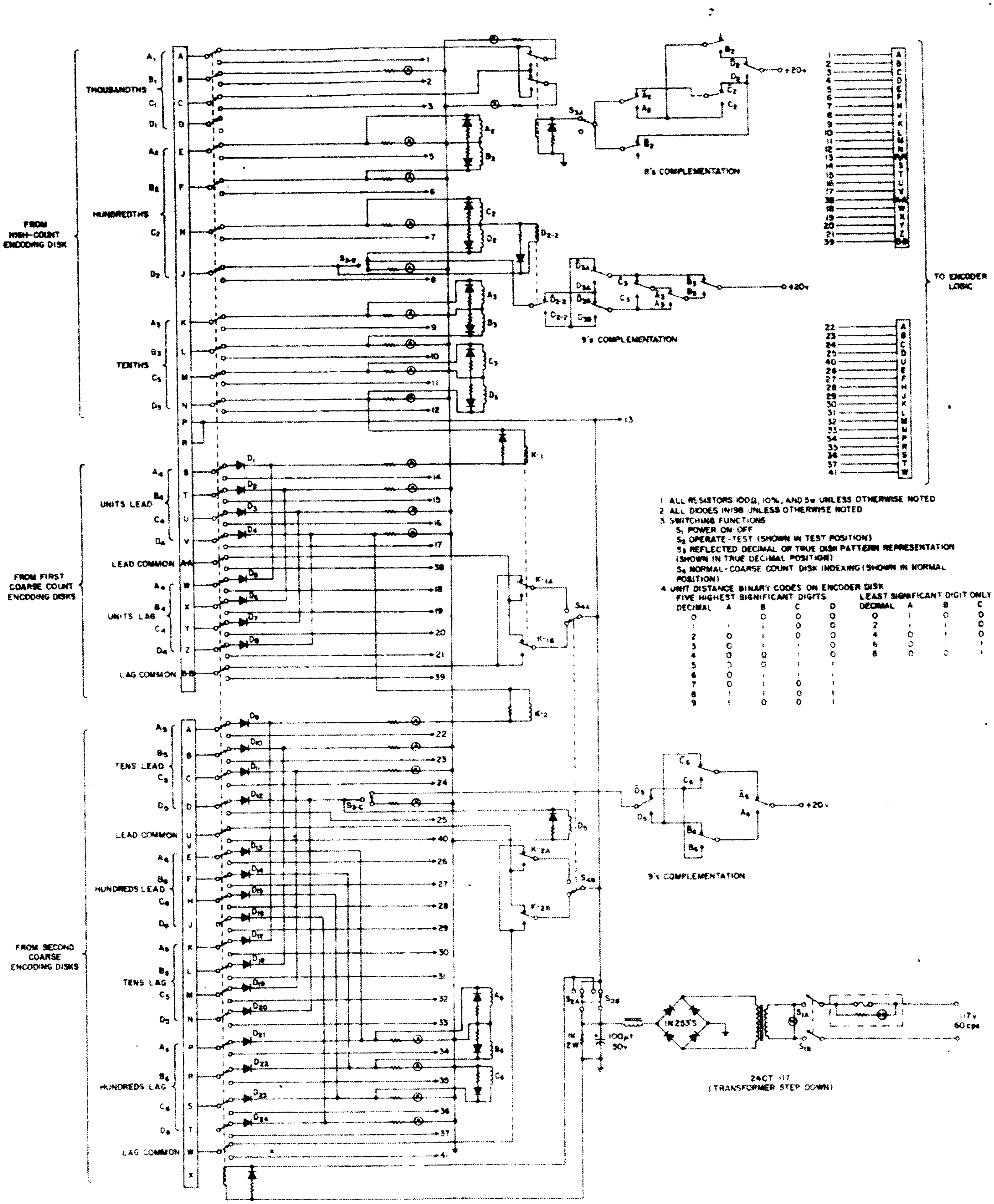


Fig. 25. Decimal encoding channel test unit, schematic diagram

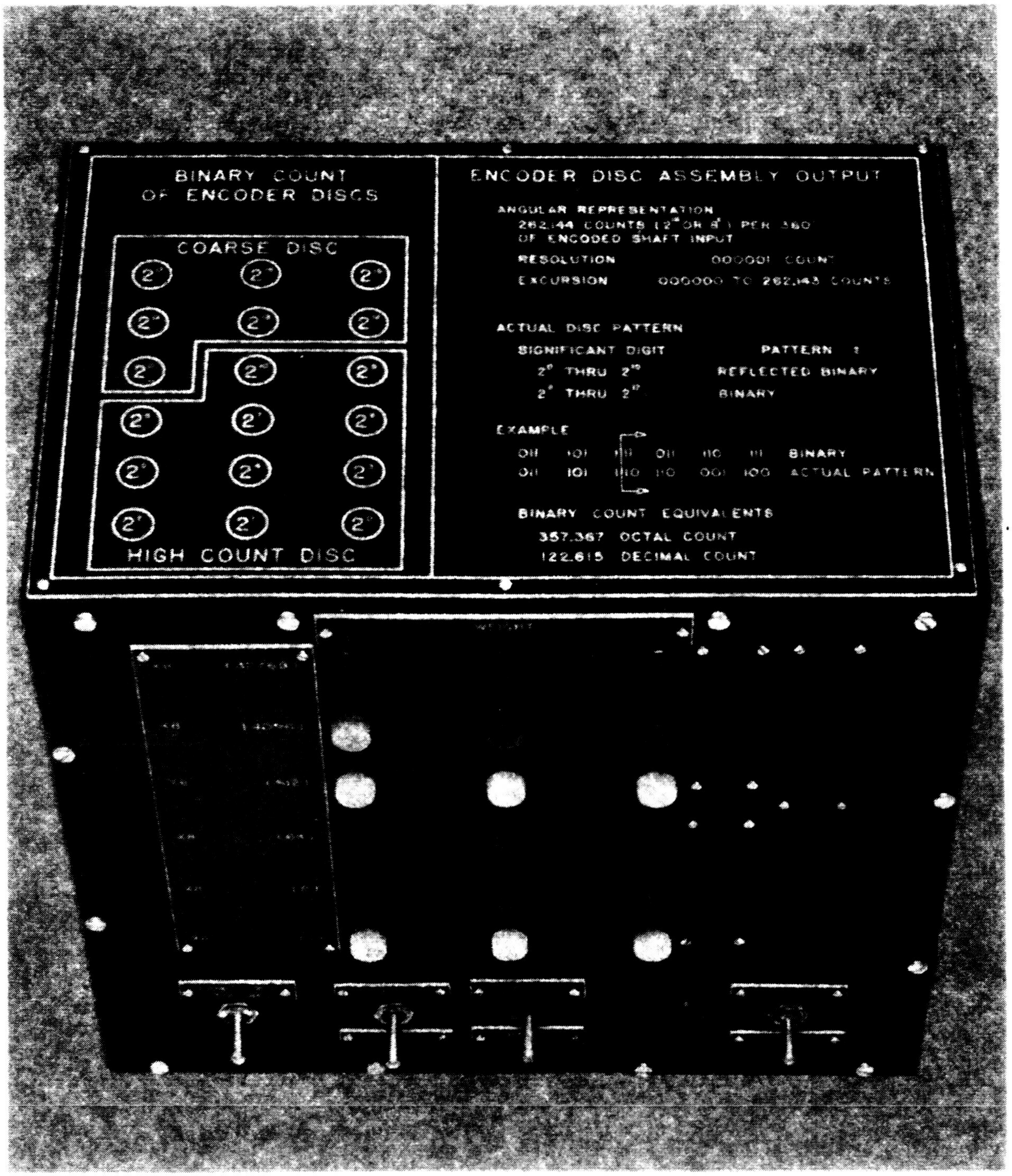


Fig. 26. Binary encoding channel-test unit

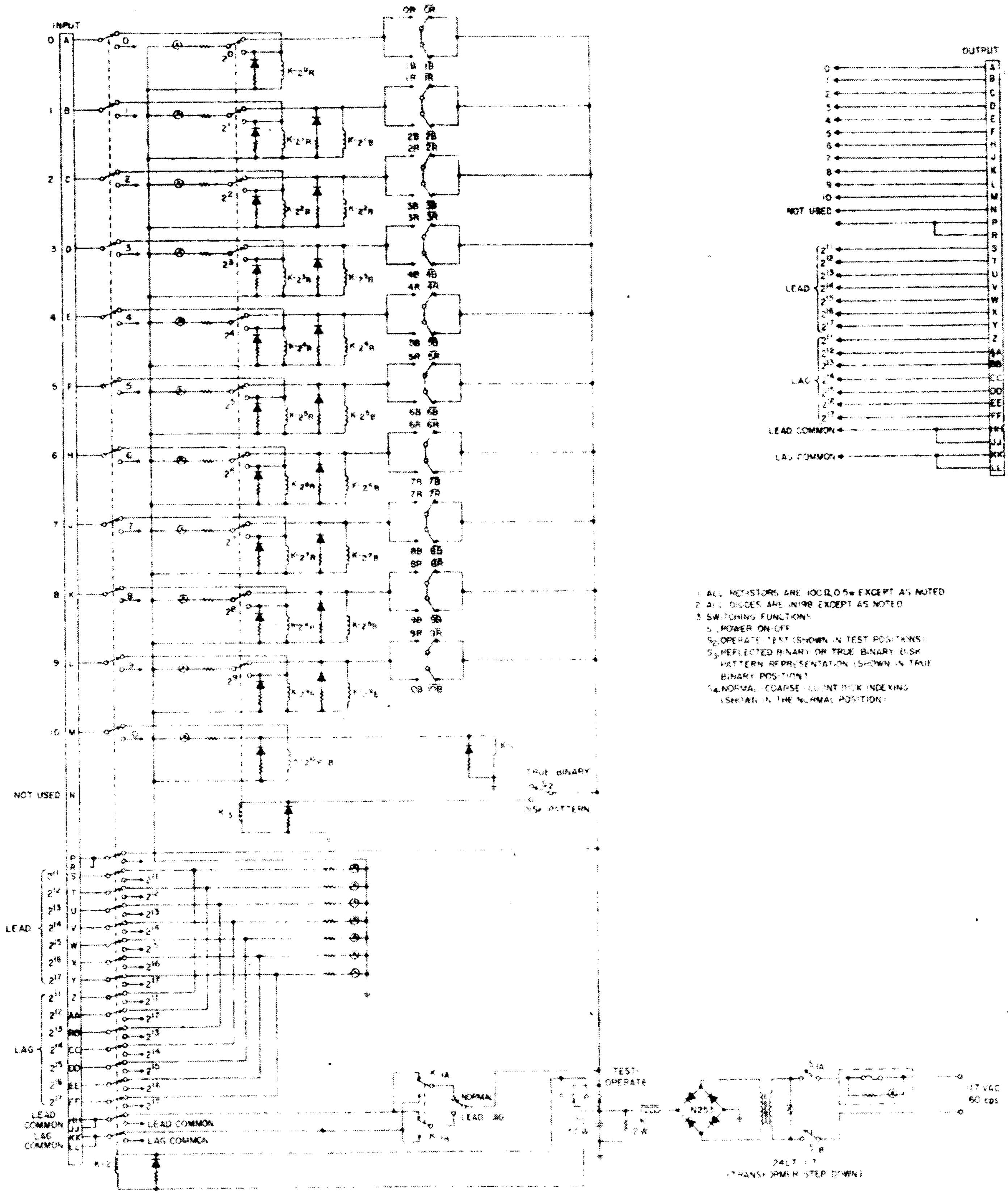


Fig. 27. Binary encoding channel test unit, schematic diagram

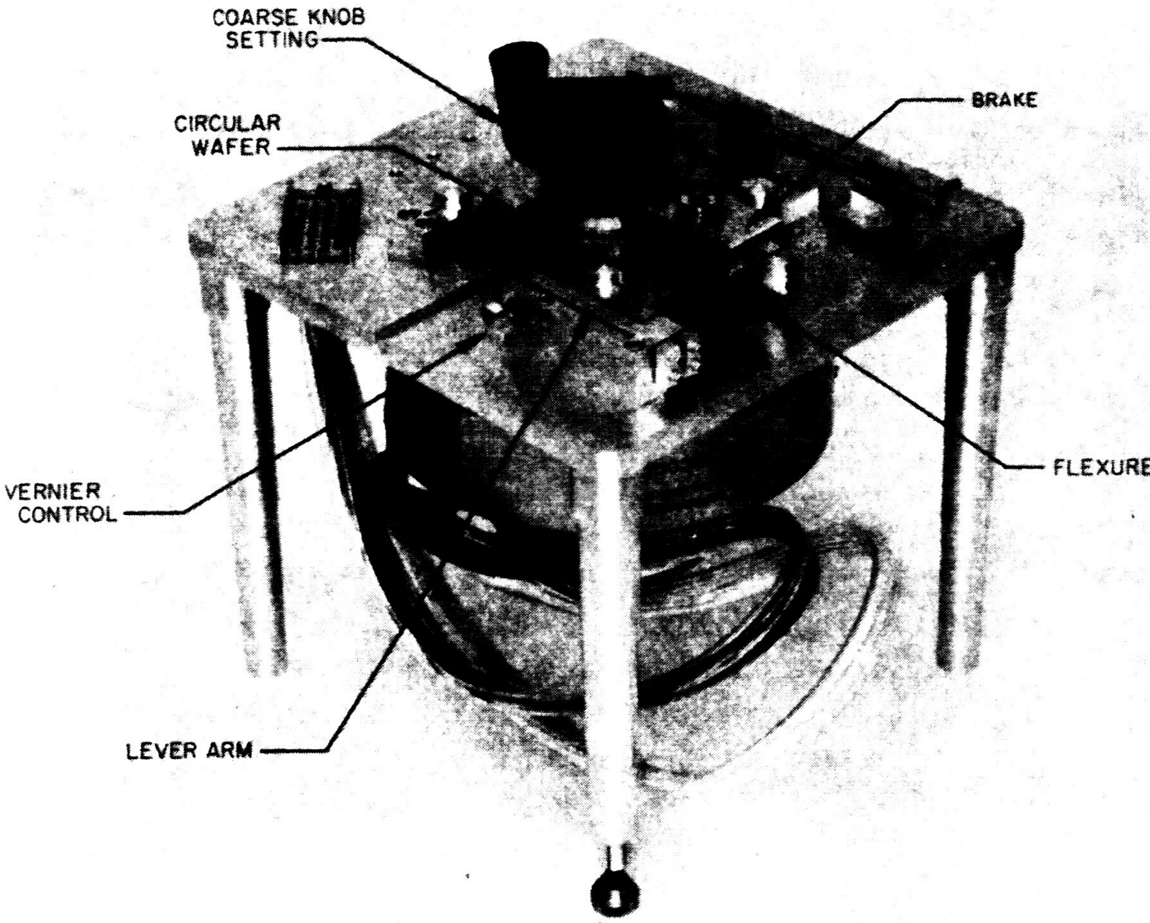


Fig. 28. Test table for encoding disk assembly

APPENDIX A

POSITIONAL NUMBERING SYSTEMS

Positional numbering systems make use of symbols (digits) to represent a number. The weight associated with the digit is specified by the position of the digit. For example, in the number 636 in the familiar decimal system, the 6 on the left has a value that is 100 times that of the 6 on the right. In general, a number is evaluated by:

$$a_n a_{n-1} \ldots a_1 a_0 . a_{-1} \ldots a_{-k} = N$$

$$= a_n \beta^n + a_{n-1} \beta^{n-1} + \ldots + a_1 \beta^1 + a_0 \beta^0 + a{-1} \beta^{-1} + \ldots + a_{-k} \beta^{-k}$$

When dealing with whole numbers, negative powers and associated coefficients (at the right of the base point) will not appear. In angular encoding, whole number representation is commonly used since the base point is fixed and therefore can be understood. The a's are the digits (whole number units) such that

$$0 \leqq a < \beta$$

where β is the base (or radix). For example, the decimal number system has a base of 10. The digits for representing any decimal number are 0, 1, 2, . . . , 9 (ten in all). The number 636 equals $6 \times 10^2 + 3 \times 10^1 + 6 \times 10^0$ or $600 + 30 + 6$.

In engineering, two-state devices such as relays (energized or de-energized), switches (on-off), vacuum tubes (conducting or nonconducting), and transistors (high-current, low-current output) are highly reliable. These devices are used to denote the presence of one of two digits.

The positional numbering system comprised of combinations of two digits (0 and 1) has a base (or radix) of 2. This is known as the binary numbering system. Binary digits are commonly referred to as bits or binits (which are contractions). The base 2 is the smallest practicable base in a positional numbering system.

Conversion to Base 10

The decimal equivalent of the binary number 110101_2 is:

$$1 \times 2^5 + 1 \times 2^4 + 0 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 1 \times 2^0$$
$$= 32 + 16 + 0 + 4 + 0 + 1 = 53_{10}$$

This same procedure can be used to convert the number of any base to the base 10. For example, the octal number (i. e., base 8) 10572_8 is equal to

$$1 \times 8^4 + 0 \times 8^3 + 5 \times 8^2 + 7 \times 8 + 2 \times 8^0$$
$$= 4096 + 0 + 320 + 56 + 2 = 4474_{10}$$

For small bases, synthetic division can be used to advantage (Ref. 18) for conversion to base 10. Instead of evaluating each term in the equivalent polynomial, one may appeal to the remainder theorem in algebra. The number 110101_2 appearing as coefficients of a polynomial in x written as

$$P(x) = x^5 + x^4 + x^2 + 1$$

for $x = 2$ equals the remainder when it is divided by $x - 2$.

By synthetic division,

$$
\begin{array}{r|rrrrrr}
2 & 1 & 1 & 0 & 1 & 0 & 1 \\
 & & 2 & 6 & 12 & 26 & 52 \\
\hline
 & 1 & 3 & 6 & 13 & 26 & 53
\end{array}
$$

As shown earlier, the remainder, 53, is the decimal equivalent of 110101_2. In general,

$$\frac{P(x)}{x - \beta} = Q(x) + \frac{r(x)}{x - \beta}$$

where

$P(x)$ is a polynomial in x

$x - \beta$ is a linear factor

$Q(x)$ is the quotient (polynomial in x)

$r(x)$ is the remainder (polynomial in x)

$$P(x) = Q(x)(x - \beta) + r(x)$$

For $x = \beta$

$P(\beta) = r(\beta)$ as stated above

Conversion from One Base to Another (Ref. 1, 18)

Let

$$N = a_n\beta^n + a_{n-1}\beta^{n-1} + \ldots + a_1\beta^1 + a_0\beta^0$$

$$= b_m\gamma^m + b_{m-1}\gamma^{m-1} + \ldots + b_1\gamma^1 + b_0\gamma^0$$

where γ is the new base and m in general does not equal n.

Dividing both expressions for N by γ

$$\frac{a_n\beta^n + a_{n-1}\beta^{n-1} + \ldots + a_1\beta^1 + a_0\beta^0}{\gamma}$$

$$= b_m\gamma^{m-1} + b_{m-1}\gamma^{m-2} + \ldots + b_1 + \frac{b_0}{\gamma}$$

Note that $b_m\gamma^{m-1} + b_{m-1}\gamma^{m-2} + \ldots + b_1 = I_0$ is an integer and the remainder, b_0/γ, is a fraction ($b_0 < \gamma$). Therefore, I_0 represents the first m terms of N (γ) divided by γ, and b_0 in the remainder b_0/γ is the least-significant digit of N in the new base γ. By dividing I_0 by γ, b_1 is found in a like manner:

$$\frac{I_0}{\gamma} = b_m\gamma^{m-2} + b_{m-1}\gamma^{m-3} + \ldots + b_2 + \frac{b_1}{\gamma}$$

Repeated divisions by γ yield $b_2, b_3, \ldots, b_{m-1}$ and b_m in that order.

For example, converting 53_{10} to a number in base 2 yields.

$$\frac{53}{2} = 26 + \frac{1}{2} \quad \text{least-significant digit}$$

$$\frac{26}{2} = 13 + \frac{0}{2}$$

$$\frac{13}{2} = 6 + \frac{1}{2}$$

$$\frac{6}{2} = 3 + \frac{0}{2}$$

$$\frac{3}{2} = 6 + \frac{1}{2}$$

$$\frac{1}{2} = 0 + \frac{1}{2}$$

Therefore, $53_{10} = 110101_2$

Converting 4474_{10} to a number in base 8 yields

$$\frac{4474}{8} = 559 + \frac{2}{8}$$

$$\frac{559}{8} = 69 + \frac{7}{8}$$

$$\frac{69}{8} = 8 + \frac{5}{8}$$

$$\frac{8}{8} = 1 + \frac{0}{8}$$

$$\frac{1}{8} = 0 + \frac{1}{8}$$

Therefore, $4474_{10} = 10572_8$. These two examples illustrate conversion of a decimal number to another base. The same algorithm applies for converting a number from any base to any other base. However, the division must be performed in the base from which the number is to be converted.

Comparison of Bases

Each digit position which forms a number in a particular base β can be filled β different ways. The digits are $0, 1, \ldots, \beta-1$ or β total. For n digit positions, each of which can be filled β different ways, a total of β^n different numbers can be formed. For example, three digit positions in base ten can form 10^3 or 1000 numbers (i. e., 0, 1, . . . , 99). The higher the base, the fewer digit positions needed to express a number. Consider $53_{10} = 110101_2$. A quantitative comparison of the number of digits positions required in a binary number to equal the maximum number n digits can form in a decimal follows:

$$2^q \geqq 10^n$$

That is, q digit positions in base 2 must be used to form as many or more numbers than n digits in base 10

$$q \log 2 \geqq n \log 10 = n$$

$$q \geqq \frac{n}{\log 2}$$

$$q \geqq 3.32\ n$$

For n = 2

$$10^n - 1 \doteq 99 \text{ (maximum base 10 number)}$$

$$q = 3.32 \times 2 \text{ or } 7 \text{ (nearest higher integer)}$$

Hence 7 binary digits are required to represent 99_{10}. As mentioned previously, two-state (stable) devices which are reliable are numerous. Though a base 10 number requires less than one-third the number of digits required by a base 2 number, ten stable states as opposed to two would be required of a physical device to represent decimal numbers. Since practical considerations dictate the use of two-state or bistable devices, the base 2 or binary is the most efficient (Ref. 19). All possible combinations of the two states of each bistable device are utilized. Using these bistable devices to code individual digits of other bases results in unused combinations. To realize ten combinations, four digit positions are necessary. Since,

$$2^3 < 10 < 2^4$$

three bits yield only 8 combinations and four give 16.

Decimal Number	Binary Representation 2^3	2^2	2^1	2^0
0	0	0	0	0
1	0	0	0	1
2	0	0	1	0
3	0	0	1	1
4	0	1	0	0
5	0	1	0	1
6	0	1	1	0
7	0	1	1	1
8	1	0	0	0
9	1	0	0	1

	Binary Representation			
	2^3	2^2	2^1	2^0
six unused combinations:	1	0	1	0
	1	0	1	1
	1	1	0	0
	1	1	0	1
	1	1	1	0
	1	1	1	1

Binary, Octal, and Binary-Coded Decimal Numbering Systems.

In computers, where memory capacity is a constraint, binary representations and arithmetic operations are invariably adopted. For n digit positions, a total of 2^n different numbers can be represented. Because of the many digit positions associated with binary representations of decimal numbers, monitoring binary numbers by an operator is most difficult. The octal system (base 8) which has a base that is a power of 2 is used to monitor binary numbers by 3-bit grouping. The digits in an octal system are 0, 1, . . . , 7. The octal number, c_n, c_{n-1}, . . . , c_1, c_0, form appears as:

$$c_n 8^n + c_{n-1} 8^{n-1} + \ldots + c_1 8^1 + c_0 8^0$$

The octal digits are the coefficients which never exceed 7. The last term, therefore, can be written as:

$$b_2 2^2 + b_1 2^1 + b_0 2^0 = c_0 8^0$$

The coefficients are binary digits and can be used in combination to represent octal digits from 0 through 7, hence c_0. Also,

$$b_5\,2^5 + b_4\,2^4 + b_3\,2^3 = c_1\,8^1$$

These binary digits (weighted as shown) can represent all octal digits (with a x8 weight). This fact can be extended for all the octal coefficients and their weights.

The conversion of a binary number to its equivalent octal can be done by inspection, whereas it is difficult to find its equivalent decimal value. After having memorized binary equivalents of 0 through 7, one may derive the octal representation of a binary number such as 10111110010 as follows:

(0)10/111/110/010 (base 2)

= 2 7 6 2 (base 8)

This usually serves as the intermediate step for binary-to-decimal conversion.

As previously discussed, binary digits can be used to represent digits of other bases. Four-bit representations of the 10 decimal digits are the permutations of 16 combinations taken 10 at a time or

$$^{16}P_{10} = \frac{16!}{(16-10)!} = \frac{16!}{6!} = 2.9 \times 10^{10}$$

As shown in Ref. 20, the essentially different codes total 7.6×10^7, and, of these, there are only 225 possible fixed-weight codes. In a fixed-weight code, the weight of a bit always corresponds to its position. The fixed-weight codes have the advantage of ease of interpretation and computation. The 8-4-2-1 (2^3, 2^2, 2^1, 2^0) group previously discussed is the only group in which every decimal digit representation is unique. In a 4-2-2-1 group, for example, only 8 and 9 have unique representations. This group can therefore be used for 32 different decimal digit codes.

In data handling, information is processed in digital form. Decimal outputs for monitoring and permanent storage purposes are very often required. The cost of conversion of binary to decimal can more than offset the saving in storage elements allowed by the use of binary representations. Binary-coded-decimal representations are, therefore, often utilized in data handling systems. The conversion of BCD to decimal is simple in terms of mechanization (Ref. 1). Both are base 10 positional numbering systems. On the other hand, conversion between bases, such as binary to BCD and BCD to binary, is not as simple, although ingenious schemes have been devised (Ref. 21). Similar arguments hold for the insertion of data in decimal or BCD form, especially when an operator is involved.

Assigning the 8-4-2-1 weights (2^3, 2^2, 2^1, 2^0) to the binary representations of decimal digits enables one to convert easily to decimal mentally. For example, $(1001\ 0101\ 0110\ 0011)_{10}$ is the BCD (8-4-2-1) equivalent of 9563_{10}.

APPENDIX B

JPL SPECIFICATION NO. 6044-A

1. SCOPE

1.1 Scope. This specification covers the design requirements for the manufacture of electromechanical equipment designated Angular Encoding System.

1.2 Application. The equipment described by this specification is designed to provide a digital representation of the angular position of an axis of the transmitting or receiving antenna operating at the JPL Goldstone Site, Camp Irwin, near Barstow, California.

2. APPLICABLE DOCUMENTS

2.1 The following documents, of the issue in effect on date of invitation for bids, form a part of this specification:

SPECIFICATIONS

Military

Mil-T-152	Treatment, moisture-and-fungus-resistant, of communications, electronic and associated electrical equipment.
Mil-C-490	Cleaning and preparation of ferrous and zinc-coated surfaces for protective coatings.
Mil-E-5272	Environmental testing, aeronautical and associated equipment, general specification for.
Mil-P-6889	Primer; zinc, aircraft use.
Mil-T-10472	Finishes for ground equipment.
Mil-E-15090	Enamel, equipment, light gray (Formula No. 11).

Jet Propulsion Laboratory

20016	Workmanship requirements for electronic equipment, general specification.
20018	Cable assemblies, fabrication of, general specification.

2.2 Other publications. The following documents form a part of this specification to the extent specified herein. Unless otherwise indicated, the issue in effect on date of invitation for bids shall apply.

Catalogue for Gray Paint, Code 530-4023, Cardinal Industrial Finishes, 11015 E. Rust Street, El Monte, California

3.1 Materials. The materials, parts, and mechanical assemblies used in construction of the angular encoding system, but not specified in detail, shall be of a quality consistent with the proposed use and specified performance of the system. Where there is any doubt as to the proper use of any material, part, or mechanical assembly, such matters shall be referred to the JPL cognizant engineer for decision.

3.1.1 Protective treatment. Where materials used are subject to deterioration when exposed to climatic and environmental conditions likely to occur during service usage, they shall be protected against such deterioration in a manner that will in no way prevent compliance with the performance requirements of this specification. The use of any protective coating that will crack, chip, or scale with age or extremes of environment shall be avoided.

3.1.2 Fungus. Materials which are not nutrients for fungus shall be used to the greatest extent practicable. Where it is necessary to use nutrient materials, they shall be suitably sealed or protected, and their use shall be subject to approval by the JPL cognizant engineer.

3.2 Design. The detailed mechanical and electrical design of the angular encoding system shall be the responsibility of the Contractor, subject to the requirements of this specification. The requirements of this specification are detailed only to the extent considered necessary to obtain the desired mechanical and electrical characteristics and performance.

3.2.1 Design change. Any change from the requirements of this specification or drawings referenced herein shall receive prior approval by JPL before incorporation in production.

3.2.2 Interchangeability. All encoding system parts and assemblies which are removable or replaceable and have the same manufacturer's part number shall be directly and completely interchangeable with respect to installation and performance except for compensation cams and multipoled synchro resolvers.

3.2.3 Convenience. Each assembly forming a part of the angular encoding system shall provide easy and ready access to its interior parts, terminals, and wiring for complete circuit checking and for the removal and replacement of parts. As a general rule it will not be acceptable to displace, or remove wires, cables, parts or assemblies in order to gain access to terminals, soldered connections, mounting screws and the like. Where it is not practicable to avoid such construction, those parts which must be displaced or removed shall be so designed, mounted, and otherwise arranged as to facilitate their displacement or removal when necessary. When in the process of checking or removing a part it is necessary to displace some other part, the latter, wherever practicable, shall be so wired and mounted that it can be moved sufficiently without disconnection from its circuit.

3.2.4 Interference. The encoding system shall incorporate maximum practicable protection from the effects of electrical and radio frequency noise and interference signals, and have provisions against the generation of undesired signals which might adversely affect other equipments operating in the same vicinity.

3.2.5 Moisture pockets. The equipment shall be constructed so that there are no pockets, wells, traps, and the like in which water and condensed moisture can collect when the equipment is in normal operating position. If this is not practicable, means shall be provided for draining the water from the pockets.

3.2.6 Cooling. Adequate means shall be employed to maintain parts within their maximum permissible operating temperature under all operating conditions.

3.2.7 Safety of personnel. The design of the angular encoding system shall be such as to provide maximum convenience and safety to personnel in installing, operating, and maintaining the equipment. Satisfactory provision shall be made to prevent personnel from accidentally coming in contact with voltages in excess of 40 volts.

3.3 Units. The angular encoding system shall comprise a sensor, a servo follow-up unit, two digital encoding disk assemblies, logic units, and visual display equipment.

3.4 Details of units. The principal units of the angular encoding system shall be designed within the following performance and product characteristics.

3.4.1 Sensor. A 27-pole synchro resolver developed by the Bell Telephone Laboratories and manufactured by the Clifton Precision Products Co., Inc., shall be directly coupled to the antenna axis to sense antenna rotation about that axis. A single-pole synchro resolver shall also be coupled to the same antenna axis to provide nonambiguous, coarse positional information. The multipoled synchro resolver is a precision transducer which functionally behaves like a geared-up synchro resolver. The angular output in electrical form is a multiple (27 to 1) of the sensed mechanical input and is derived electrically.

3.4.2 Servo follow-up. A servo-follow unit shall be located in a building approximately 100 ft (in terms of cable run) from the synchro resolvers which serve to provide electrical gearing power which will result in a servo output shaft rotation 27 times that of the input shaft rotation (antenna axis). In addition to feedback proportional to the output shaft position, inertial damping proportional to the output shaft's angular acceleration shall be incorporated in the servo follow-up. The maximum angular velocity of the input shaft (antenna axis) will be 4°/sec. The maximum angular acceleration of the input shaft (antenna axis) will be $5°/sec^2$.

3.4.3 Digital encoder disk assemblies. Geared to the output shaft of the servo follow-up shall be two digital encoder disk assemblies. For one revolution of an axis of the antenna, one disk assembly shall provide a 180,000 output count while the other shall provide a 262,144 output count. Cyclic code patterns or nonambiguous logic shall be used to reduce count ambiguity to ± 1 count in the region of count transition. The 180,000 count disk-assembly shall be coded in cyclic decimal and the 262,144 count (2^{18}) disk assembly shall be coded in cyclic binary. Nickel, rhodium, and gold plating shall be used in the conducting segments of the disk pattern. Compensation cams shall be provided to reduce the effects of fixed system errors. The housing and brushes of the high count disk of each assembly shall be made to undergo angular positional changes proportional to the compensation cam profile.

3.4.4 Logic. Transistorized logic shall be provided for each encoder disk assembly. The logic associated with a cyclic decimal input shall provide decimal and binary-coded-decimal outputs. The logic associated with a cyclic binary input shall provide a binary output.

3.4.4.1 Readout command and readout command rates. Upon the receipt of a readout command (interrogation signal) consisting of a -16 volt dc level of a 25-microsec duration (or greater), the logic will follow the output of an associated disk assembly for the duration of the readout command. For the subsequent 110 microsec, the logic will cease to follow the disk assembly output, thus providing transistor settling time. After 135 microsec, the stored angular data shall be available for readout. Angular data shall remain stored until the next readout command (interrogation signal). The readout command rates will be as follows:

(a) Decimal Encoding

No greater than one (1) readout command per sec.

(b) Binary Encoding

No greater than 1024 readout commands per sec.

3.4.4.2 Logic outputs. Outputs of the logic units shall be as follows:

3.4.4.2.1 Decimal encoding.

(a) One (1) binary-coded-decimal output (four wires per digit plus a shared common) shall be provided. Nominal levels for binary representations shall be either of two sets.

Binary representation	Nominal voltage level	
True (1)	-6 v	-13 v
False (0)	-0 v	-23 v

The logic shall be capable of providing either of the two sets of voltage levels. Reference levels where needed will be supplied externally. The binary-coded-decimal output shall be capable of representing angular data varying from 000000 to 359998 deg in increments of 000002 deg.

(b) One (1) decimal output (ten wires per digit plus a shared common)shall be provided to drive an Industrial Electronic Engineers type in-line lamp bank for visual display purposes. The lamp bank assembly shall be provided by the Contractor. The decimal degree representation shall be capable of varying from 000000 to 359998 deg in 000002 deg increments.

3.4.4.2.2 Binary encoding. One (1) binary output (one wire per digit plus a shared common) shall be provided. Voltage levels for binary representations shall be:

Binary representation	Voltage level
True (1)	-(1.5 v or greater)
False (0)	0 ± 0.5 v

The binary output shall be capable of representing a count from 000000 to 262,143 in 000001 increments.

3.4.4.2.3 Future logic output capability. Provisions shall be included in the logic associated with decimal encoding to enable the output increment to be halved (i.e., double the resolution). By changing modular logic boards associated with the least-significant digit (together with the pattern on the high count disk, the disk assembly, and its step-up drive ratio), output capability for decimal encoding shall be 000000 to 359999 deg in 000001 deg increments.

3.4.4.3 Modular logic board layout. The modular logic board layout shall be such that it results in accessibility to the individual boards from the front or the face of the rack mounted logic. Two extension test boards shall be provided for each logic unit.

3.5 Performance. The accuracy requirement of the encoding system shall be 20 sec of arc rms, or better. The design accuracy goal shall be 10 sec of arc rms, or better. This includes the effects of the sensor, servo follow-up, and encoder disk assembly. The logic shall convert the digital cyclic input count to the required outputs (see 3.4.4.2) without introducing any error. The above accuracy shall apply for antenna angular rates not exceeding one deg per sec.

3.6 Fabrication. The Contractor shall fabricate or supply hardware for mounting and packaging the servo follow-up and encoding disk assemblies. Precision gearing for the servo follow-up output shall be provided by the Contractor. The Contractor shall fabricate or supply hardware for mounting, coupling, and packaging the synchro resolvers at the polar and declination shafts of the receiving antenna. Dimensioned mechanical drawings of allocated mounting space for the resolvers and their coupling will be furnished by JPL.

3.6.1 Miniature, Style CB with engaging clamps, Thomas Couplers manufactured by the Thomas Flexible Coupling Co., Warren, Pennsylvania, shall be used throughout. Lateral misalignment of shafts to be coupled by means of a Thomas coupler shall not exceed 0.028 in.

3.6.2 The housing and coupling for the synchro resolvers at the transmitter antenna will be supplied by the Blaw-Knox Company, Pittsburgh, Pennsylvania. The Contractor shall be responsible for supplying hardware to mount the synchro resolvers at the transmitter antenna.

3.7 Cabling. All interconnecting cabling between units, including the sensor, servo follow-up, encoder disk assembly and logic shall be supplied by the Contractor. The Contractor shall also supply cabling to accommodate the outputs of the logic and to furnish primary input power to the above units where required. All cable assemblies shall be fabricated in accordance with JPL Specification No. 20018.

3.8 Connectors. The Contractor shall supply all connectors. The following types shall be used for interconnection cabling:

Function	Manufacturer	Type
Sensor signal and power	Amphenol	89-228-16P 80-128-16S
Servo and logic primary power	Cannon, Amphenol, or Bendix	AN-3102-E-14S-6P AN-3106-E-14S-6S
Servo and logic signal	Consolidated Electrodynamics (CEC)	Multi-contact Series 500-C
Logic interrogation signal		BNC UG-290/U UG- 88/U.

3.8.1 Special tools required for mating Type CEC connectors with conductors shall be purchased by the Contractor and supplied to JPL upon completion of the contract.

3.9 Primary power. The following primary ac voltages will be available at each antenna site:

120 v ± 10% at 60 ± 0.5 cps

120 v ± 10% at 400 ± 2.5 cps

3.10 Racks and installation. Standard racks will be available for the logic associated with the axes of the receiving antenna. All other equipment racks shall be supplied by the Contractor. The racks for the logic associated with the transmitting antenna shall be Model FC1-24V-77-P (cooling fans included) manufactured by: Western Devices, 600 N. Florence Avenue, Inglewood, California.

3.10.1 Panels. Blank racks panels where needed shall be supplied by the Contractor.

3.10.2 Servo follow-up units. Industrial type racks shall be used to house the servo follow-up units.

3.10.3 Rack finishing. Racks shall be finished with gray paint Code 530-4023, manufactured by: Cardinal Industrial Finishes, 11015 East Rush Street, El Monte, California, or Formula No. 11 - light gray, equipment enamel, Mil-E-15090.

3.11 Special tools. Any nonstandard tools required for operation or maintenance of the angular encoding system shall be furnished by the Contractor with each equipment.

3.12 Environmental and service conditions. The angular encoding system shall be so designed and constructed that no fixed part or assembly shall become loose, no movable part shall become undesirably free in operation, and no degradation of performance shall be caused when subjected to the following ambient conditions:

Temperature	-25 to 135°F (sensor, servo follow-up and disk assembly)
	25 to 135°F (other)
Humidity	0.'0 to 95%
Altitude	0 to 5000 ft
Transportation	When nonoperating and packed for shipment, and subject to the rigors of air freight, railroad, or trucking, the equipment shall function properly upon reaching its destination.

3.12.1 The logic units will be housed in a temperature-controlled building. The disk assembly will be housed in an enclosed shelter which is not temperature controlled. The sensors will be located on the antennas as an enclosed package.

3.13 Workmanship. The angular encoding system shall be assembled in a thoroughly workmanlike manner in accordance with JPL Specification 20016.

4. QUALITY ASSURANCE PROVISIONS

4.1 Contractor's inspection and test. The Contractor's factory inspection shall include such visual, electrical and mechanical examination and testing of materials, subassemblies, parts and accessories, including source items, during the process of manufacture as may be required to assure that the complete equipment will meet all the requirements of this specification.

4.2 Accuracy test. Each angular encoding system shall be tested for accuracy at the Contractor's facility prior to on-site installation. The accuracy test shall be conducted by the Contractor under JPL supervision, and shall include a thorough visual and mechanical examination as well as the following accuracy test:

(a) The input shaft of the multipoled synchro resolver shall be positioned (throughout 360 deg of rotation) to provide a minimum of 100 output counts (in equal increments) for each encoder disk assembly.

(b) The difference between the angle represented by each count (at the transition from the next lower count to the count in question) and the angular position of the input shaft shall be determined.

(c) Input shaft angles shall be measured with a device having an absolute accuracy of two (2) sec of arc or better. An indexing head calibrated with an auto-collimator or a T-3 theodolite may be used to meet this accuracy requirement.

(d) These measurements shall be used to calculate the sample mean and rms errors as shown below:

$$X^* = \frac{1}{n}\sum_{k=1}^{n}\left(X_{k_s} - X_k\right)$$

$$S^* = \sqrt{\frac{1}{n}\sum_{k=1}^{n}\left[X^* - \left(X_{k_s} - X_k\right)\right]^2}$$

where

X^* = the sample mean error

X_{k_s} = kth reading of angle represented by encoder output count

X_k = kth reading of the angular position of input shaft of multipoled synchro resolver

S^* = the rms error about the sample mean error

n = 100 or greater

(e) The above tests shall be repeated for each disk assembly alone.

(f) The angular position of the input shaft of the encoder assembly shall be measured in the same manner as prescribed for the multipoled synchro resolver. This measurement shall be referenced to the antenna axis assuming ideal coupling and ideal gearing such that:

$$X_k = X_{k_e}/90 \text{ for decimal encoding}$$

$$X_k = X_{k_e}/128 \text{ for binary encoding}$$

where

X_{k_e} = kth reading of the angular position of the input shaft of the encoder disk assembly.

4.2.1 Acceptance test. Each angular encoding system will be subjected to an operational check by JPL upon its arrival at the site. The operational test will constitute an acceptance test, the purpose of which is to insure equipment is in proper functional operating condition after shipment to the site.

4.4 Rejection and retest. Encoding systems or assemblies which have been rejected or returned may be reworked or have parts replaced to correct defects, and resubmitted for acceptance. Full particulars concerning the rejection and the action taken to correct the defects shall be furnished the JPL cognizant engineer before resubmittal.

5. PREPARATION FOR DELIVERY

5.1 Preservation, packaging, and packing. Unless otherwise specified, the equipments shall be prepared for delivery in conformance with good commercial practices for domestic handling by truck transportation.

6. NOTES

6.1 Intended use. The angular encoding system covered by this specification is intended for use at the JPL Goldstone Site, Camp Irwin, near Barstow, California. Four (4) complete angular encoding systems will be installed to provide digital representations of the angular position of each of two axes of the Goldstone transmitting and receiving antennae.

APPENDIX C

REFLECTED CODES

The angular encoding disk shown in Fig. C-1 illustrates the commutator type utilizing photoengraved conducting and nonconducting segments to represent true binary numbers. The dark areas represent conducting material and the light areas nonconducting material. The conducting segments are actually raised portions of a solid metallic disk. The finished disk is pressed and polished to a smooth surface of conducting and nonconducting segments. The brushes are stationary relative to disk rotation. The innermost circular track is a conductive ring and its associated brush is electrically common to all conducting segments. By connecting the common brush to a voltage source, brushes riding on conducting segments will be at that voltage while those on nonconducting segments are at zero potential. Thus, the two level binary-digit representations are realized. The four outermost tracks ride on tracks called zones. The least significant bit, 2^0, is represented by the outermost zone. Segments in this zone determine the encoding disk resolution. The brushes A, B, C, D are sensing the binary equivalent of the decimal-digit.

Assume that the shaft is rotated counter clockwise. At the count transition, 7 to 8, all four brushes are required to simultaneously sense a new voltage level representing a change in each binary digit as shown.

	2^3	2^2	2^1	2^0
Decimal count	A	B	C	D
7	0	1	1	1
8	1	0	0	0

Since the brushes cannot be perfectly aligned, the disk cannot be mounted without some eccentricity, and the segments cannot be ruled perfectly, brushes A, B, C, D will not simultaneously sense a change in state. Brush A, for example, could conceivably sense a change before B, C, and D, which would result in a jump from 0111 to 1111 or 7 to 16 before the transition is completed. Because of the aforementioned physical limitations, a class of variable-weight codes can be used to advantage.

To reduce the ambiguity in the region of count transition to ± 1 count, a reflected binary devised by F. Gray is employed. A reflected binary code has a unit distance property. Representations of adjacent numbers differ by only a 1- bit change in one and only one digit position. The title "reflected binary" is a result of a method of generating the code. Starting with a binary 0 followed by a binary 1 in a column, a mirror image, 1 and 0, is added to the column. To distinguish 0, 1 from its image 1, 0, zeros are placed before the former and ones before the latter.

Decimal	Reflected Binary
0	0 0
1	0 1
2	1 1
3	1 0

This results in reflected binary representations of 0, 1, 2, and 3. Note that adjacent digits differ by only 1 bit. By making another reflection (for both columns) and properly placing zeros and ones in a new column, the reflected code is extended. Reflected binary for 16 counts is shown as follows:

Decimal	Reflected Binary ABCD
0	0 0 0 0
1	0 0 0 1
2	0 0 1 1
3	0 0 1 0
4	0 1 1 0
5	0 1 1 1
6	0 1 0 1
7	0 1 0 0
8	1 1 0 0
9	1 1 0 1
10	1 1 1 1
11	1 1 1 0
12	1 0 1 0
13	1 0 1 1
14	1 0 0 1
15	1 0 0 0

Codes exhibiting this unit-distance property at transition are also referred to as unit-distance, cyclic, monostrophic, or progressive codes. Unit distance codes can be generated with the aid of a Karnaugh map (Ref. 23) as will be shown subsequently.

The reflected binary is used, however, when a natural binary representation is desired. This is because of the simplicity of serial conversion of reflected binary to binary.

Note that the reflected binary is a variable-weight code. The weight of a digit cannot be determined by its position. Although it is possible mathematically to express the decimal value in terms of the binary digits, it is easier to convert the reflected binary to a natural binary and then to determine its value.

When a reflected binary pattern is used on an encoding disk, the total count must be a power of 2 to have unit-distance closure between the highest count and the zero count. There is, for example, unit-distance closure for 16 counts (2^4). The decimal number 15 (the 16th or highest count) is 1000 and 0 is 0000, so that they differ in the A-bit only. A 16-count reflected binary pattern is shown in Fig. C-2.

A reflected binary code is advantageous in that segment width representing the least-significant count may be double the size of that associated with a binary code. The resolution of a reflected binary coded disk is twice that of a binary coded disk of identical size for a given minimum segment width (see Fig. C-1, C-2).

Reflected Decimal

Reflected codes can be formed in any base (Ref. 1, 22) by using the procedure in Part A. Portions of several decades of decimal numbers and their reflected decimal equivalents are shown as follows:

Decimal	Reflected Decimal
00	00
01	01
02	02
..	..
..	..
09	09
10	19
11	18
.	.
.	.
19	10
20	20
21	21
.	.
.	.
.	.
099	090
100	190
.	.
.	.
110	189

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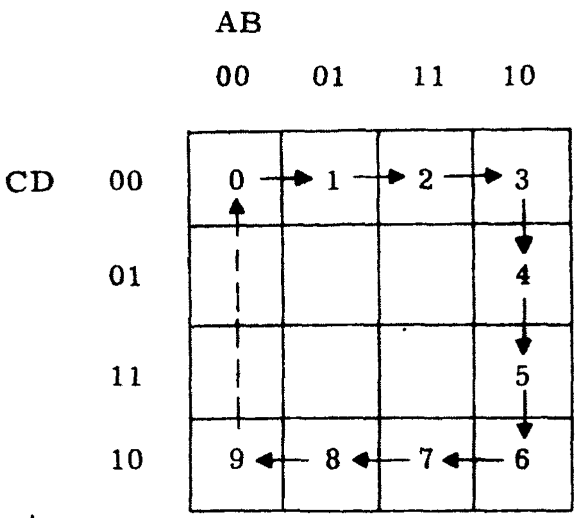
Reflection is made after each decade, and the least-significant digit is a mirror image of those in the preceding decade with the next-higher-order digit differing by one (until decimal 100 is reached and reflection in two digits is started). Note that in the decimal count transition from 09 (end of decade) to 10 involves changes in both digit positions; the reflected decimal equivalent 09 to 19 involves only one digit change.

The reflected binary equivalents of decimal numbers are not suitable for binary-coded decimal (reflected) representations since there is not a unit distance between 9 and 0 (1101 to 0000 has three bit changes). It is necessary to have unit-distance closure between the highest count and zero count in one or successive patterns on one disk.

A Karnaugh map (Ref. 23) can be used to determine a unit-distance code suitable for decimal digit representation. Contrasted to the four-bit reflected binary code where all combinations (2^4) are used, only 10 combinations are used. The former is known as a complete unit-distance code and the latter an incomplete unit-distance code.



Karnaugh Map

Each square in the Karnaugh map is identified by one of the 16 combinations of binary digits the variables A, B, C, D represent. The upper-righthand cell represents the combination 1000. Horizontally adjacent cells, including cells at opposite ends of a row, differ in one bit only (A or B). Vertically adjacent cells, including those at opposite ends of a column, differ in one bit only (C or D).

By selecting ten cells to represent the decimal digits such that successive digits are in adjacent cells, a unit-distance, binary-coded decimal system with decade closure results. The above example gives:

Decimal Number	Unit-Distance Code A	B	C	D
0	0	0	0	0
1	0	1	0	0
2	1	1	0	0
3	1	0	0	0
4	1	0	0	1
5	1	0	1	1
6	1	0	1	0
7	1	1	1	0
8	0	1	1	0
9	0	0	1	0

Conversion between Reflected and Positional Numbering Systems

1. Reflected decimal and decimal. Note that in the tabulation of decimal and corresponding reflected decimal numbers in Section B, only those digits in the

decimal number where the next-higher-order digit is odd differ from the corresponding digits in the reflected decimal number. For example,

Decimal	Reflected Decimal
$1\underline{0}$	$1\underline{9}$
$1\underline{1}$	$1\underline{8}$
.	.
.	.
$1\underline{9}$	$1\underline{0}$
.	.
.	.
.	.
.	.
$09\underline{9}$	$19\underline{0}$
$1\underline{0}0$	$1\underline{9}0$
.	.
.	.
$1\underline{10}$	$1\underline{89}$

Adding corresponding digits which differ gives a total of 9. Those cases in which the next-higher-order digit is even in the decimal number result in an identical corresponding digit in the reflected decimal equivalent. For example,

Decimal	Reflected Decimal
01	01
.	.
.	.
.	.
$0\underline{9}$	$0\underline{9}$
.	.
.	.
$2\underline{0}$	$2\underline{0}$
$2\underline{1}$	$2\underline{1}$
.	.
.	.
$10\underline{0}$	$19\underline{0}$

Since all highest significant digits are preceded by a zero (even), they are the same in decimal and reflected decimal.

Rules for converting between decimal and reflected decimal are summarized as follows:

1. The highest significant digit remains unchanged.
2. Digits whose next-higher-order digit in the decimal number is even remain unchanged.
3. Digits whose next-higher-order digit in the decimal number is odd are 9's complemented to determine the corresponding digit. (The 9's complement of a digit is the difference between the digit and 9.)

The conversion from a reflected decimal to a decimal number is as follows:

$$
\begin{array}{cccccccl}
1 & 7 & 6 & 5 & 2 & 0 & & \text{(reflected)} \\
\hline
1 & 2 & 6 & 5 & 7 & 9 & & \text{(decimal)}
\end{array}
$$

The highest significant digit, 1, is unchanged. The digits 7, 2, and 0 are 9-complemented since the next-higher-order corresponding digits in the decimal number are odd.

The conversion from a decimal to a reflected decimal number is shown as follows:

$$
\begin{array}{cccccccl}
2 & 7 \leftarrow & 1 \leftarrow & 4 & 3 \leftarrow & 6 & & \text{(decimal)} \\
\hline
2 & 7 & 8 & 5 & 3 & 3 & & \text{(reflected decimal)}
\end{array}
$$

The highest significant digit, 2, is unchanged. The digits 1, 4, and 6 are 9-complemented, since the next-higher-order decimal digit is odd.

The same procedure follows for any base. The highest digit in the base, $\beta-1$, is the digit used in the complement rule.

2. <u>Reflected binary and binary</u>.

Here, (binary) digits are 1's complemented when the next-higher-order digit in the binary number is odd or 1. A 1's complement is simply an inversion. Conversion from reflected binary to binary and vice versa is demonstrated.

1 1 0 1 1 0 1 1 (reflected binary)

1 0 0 1 0 0 1 0 (binary).

$1 \leftarrow 0 \quad 1 \leftarrow 1 \leftarrow 0 \quad 1 \leftarrow 1 \leftarrow 0$ (binary)

1 1 1 0 1 1 0 1 (reflected binary)

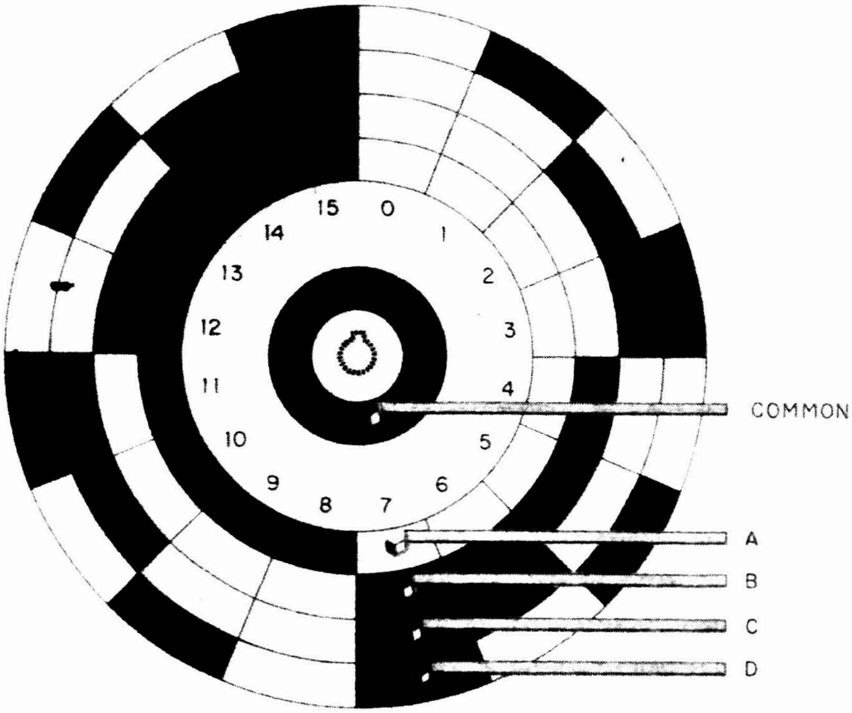


Fig. C-1. Binary coded disk

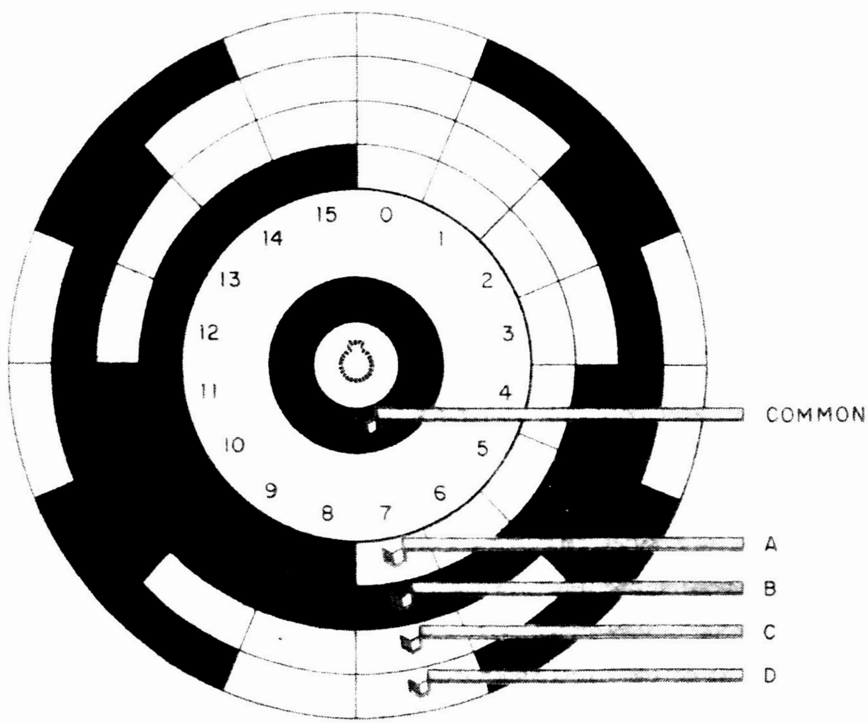


Fig. C-2. Reflected binary coded disk

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